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Evaluation of Laser Profile and Deflection Measuring System

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16. Abstract

This study evaluates the use of lasers mounted on a 10-ft beam to measure pavement profiles and deflections near a loaded wheel. The lasers require no contact with the pavement surface. The algorithm for solution of the profile is presented along with the solutions for calibrating the system. The system is a promising tool for measuring surface roughness. Continued research is required to improve the system to provide the required accuracy.

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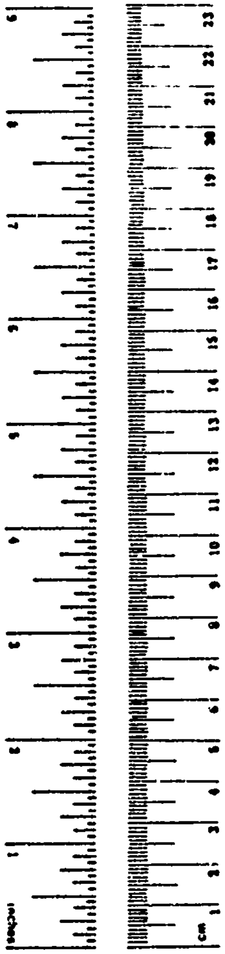
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

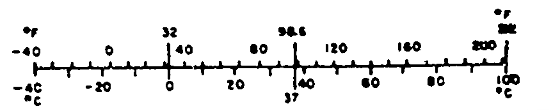
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.5	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* 1 in. = 2.54 (exactly). For other exact conversions and more detailed tables see NBC Misc. Publ. 286, Units of Weights and Measures. Price $2.25, SD Catalog No. C13 10 286.



Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

This investigation was conducted by the Geotechnical Laboratory (GL), US Army Engineer Waterways Experiment Station, during the period August 1981-March 1984. This study was cosponsored by the US Air Force Engineering and Services Center (AFESC), Tyndall AFB, Fla., under Military Interdepartmental Purchase Request (MIPR) No. N-82-41 and MIPR No. F-82-95 and by the Federal Aviation Administration (FAA) under Inter-Agency Agreement No. DTFA01-81-Y-10584. AFESC project officers for this study were Captain J. D. Wilson and Captain Norm Hanna. Mr. Fred Horn was the FAA technical monitor.

The study was conducted under the general supervision of Dr. W. F. Marcuson III, Chief, GL; Dr. T. D. White, Chief, Pavement Systems Division (PSD) GL; and Mr. J. W. Hall, Jr., Chief Engineering Investigations, Testing, and Validation Unit, GL. Personnel who took part in the study were Messrs. A. J. Bush III, R. W. Grau, T. P. Williams, and D. D. Mathews, PSD, and Mr. C. B. Cox, Instrumentation Services Division, WES. This report was prepared by Messrs. Bush and Cox.

Commanders and Directors of the WES during this investigation and preparation of this report were COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

INTRODUCTION

BACKGROUND

The ability to measure a road or airfield pavement profile rapidly and accurately offers can excellent tool for evaluation and management of a pavement network. Roughness is the major descriptor of pavement performance from the viewpoint of the pavement users whether it be a pilot or passenger in an airplane or a driver or passenger in an automobile. The deflection of the pavement surface under a known applied load is one of the best indicators to the pavement engineer as to the structural capacity of the pavement and is used to estimate that aspect of performance.

A system that can be used to measure both roughness and deflection under a moving load would advance the state of the art in pavement evaluation and pavement management. Professor M. E. Harr of Purdue University and a series of graduate students over the past 10 years have been researching the use of the deflection basin to evaluate the load-carrying capability of airfield pavements.[1-6] Initially, linear variable differential transducers (LVDT's) were placed in the pavement to measure the pavement surface deflection basin from a moving aircraft load relative to anchor points initially set 1.3, 3, 10, and 17.4 ft below the pavement surface. Because placing LVDT's in the pavement was difficult, expensive, and practical for only spot elevations, a system was needed to rapidly evaluate the full length of a runway. The LVDT's were then mounted on a 9-foot-long stiff cantilever beam supported on one end by a base and counterweight. The wheel load moved perpendicular to the beam.[4] A second beam was constructed using light-emitting diodes (LED's) which cause coherent light to reflect from the pavement onto deflectors.[5] As the pavement deflects, the reflected light registers on the detector. Because of the effects of ambient light on the LED system, a system using lasers was investigated.

The Transportation Road Research Laboratory (TRRL), Crowthorne, Great Britain, has developed a high-speed profilometer using four lasers mounted on a two-wheel trailer coupled to a towing vehicle.[7] The system is dynamic since there is no contact with a fixed reference point. The beam rotates on the axis of the two-wheel trailer and moves vertically with the wheels of the trailer. An algorithm was derived by TRRL to tie the measured profile to a fixed reference plane. The solution for the noncontact profile measurement developed by TRRL was initially used in this project.

OBJECTIVE AND SCOPE

The objective of this project is to evaluate the current capability and the potential of the laser noncontact deflection and profile-measuring system for use in the evaluation of airfield pavements. Additionally, recommendations for further development are made.

The research described herein includes the development of the software to control the laser system as well as collect the data. The equipment was demonstrated under field conditions and results compared to measured profiles. The work described herein is a joint effort between the US Army Engineer Waterways Experiment Station and Purdue University. The initial effort was reported by Elton and included the selection of equipment and reported the initial data collected.[6] This report covers modifications to the initial system in both hardware and software and additional data acquired.

DESCRIPTION OF THE PROFILING SYSTEM

LASERS

The light amplification by stimulated emission of radiation (laser) devices used in this study are mounted on a rigid beam and measure the distance from the beam to the pavement surface. The lasers require no contact with the surface. The infrared light source is projected through a lens to the pavement surface (Figure 1). A portion of the light is scattered and received through another lens on a strip of photosensitive material. The position at which the light beam strikes the photosensitive material is proportional to the distance to the surface. Specifications for the lasers are given in Table 1.

MOUNTING

The lasers are mounted on a rigid beam designed to minimize bending (Figure 2) so the gages will remain fixed relative to each other. The length of beam is important in deflection measurement because the lasers measuring the undeflected profile must be out of the deflection basin caused by the loaded wheel. The configuration selected is a 10-ft beam with 9 ft between gages 1 and 4 and a 1-ft interval between gages 1, 2, and 3 (Figure 3). When tests were made to evaluate only the profiling capability, all four lasers were mounted 1 ft apart. The beam is attached to the vehicle on a mounting system with a set of springs with the stiffness of the springs less than the stiffness of the beam, which reduces bending in the beam from vibrations.

MEASURING WHEEL

The distance the profilometer travels is one of the controlling inputs to the acquisition program. This distance is acquired by a measuring wheel (Figure 4). This wheel is mounted on the back of the profilometer vehicle and is 84 in. (2.1336 m) in circumference. The shaft of the wheel is connected to an optical encoder that delivers a voltage change every 2 in. The accuracy of the wheel is approximately 1 percent.

THREE-WHEEL CART

In order to calibrate the system with all lasers outside an area that was deflected by a loaded wheel a cart was constructed (Figure 5). The construction consisted of three bicycle tires and a 6-in. by 1-in. aluminum box beam. The cart could be pulled by hand over a premeasured profile without the influence of a loaded wheel.

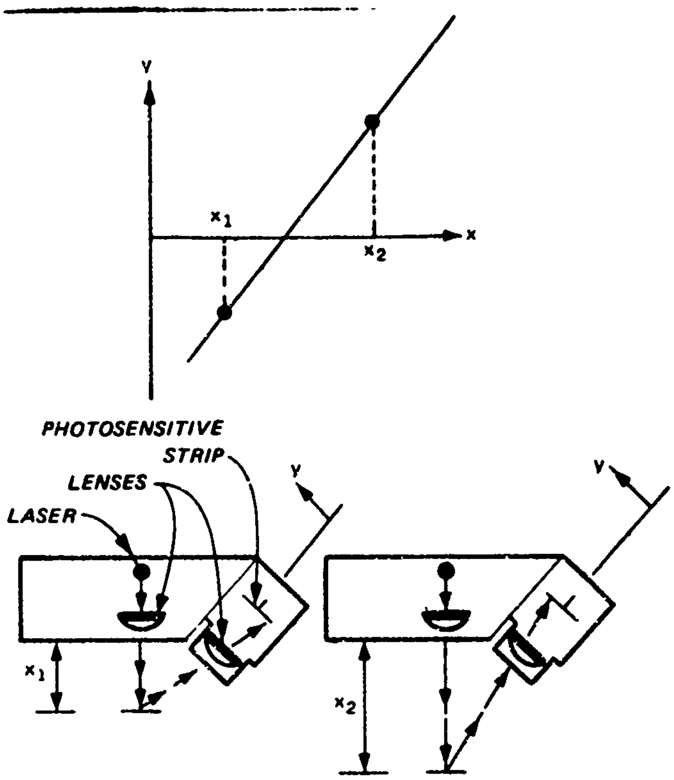


Figure 1. Laser measurement method

Table 1. General Specifications for Laser

Scale factor:	32 micrometers per bit
Standoff distance:	95 mm (3.7 in.) to 300 mm (12 in.)
Measuring range:	128 mm (5.0 in.)
Accuracy:	±0.05 percent of measuring range
Resolution:	0.025 percent of measuring range
Nonlinearity:	±0.05 percent of measuring range
Sampling frequency:	16 kHz
Laser output power:	Maximum 4 mw
Wavelength:	850 nm
Digital output:	12 bit

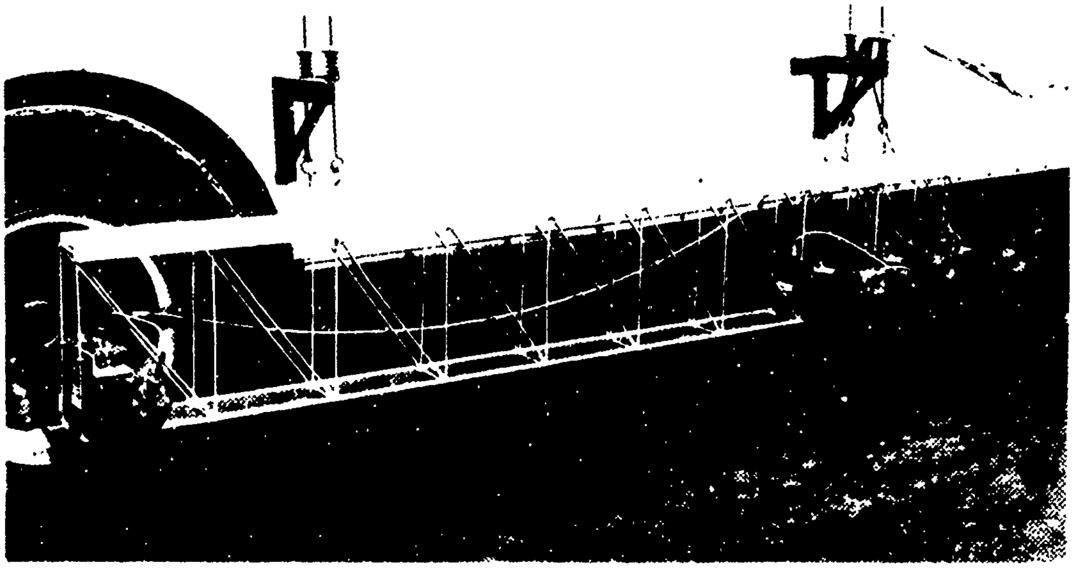


Figure 2. Laser profilometer

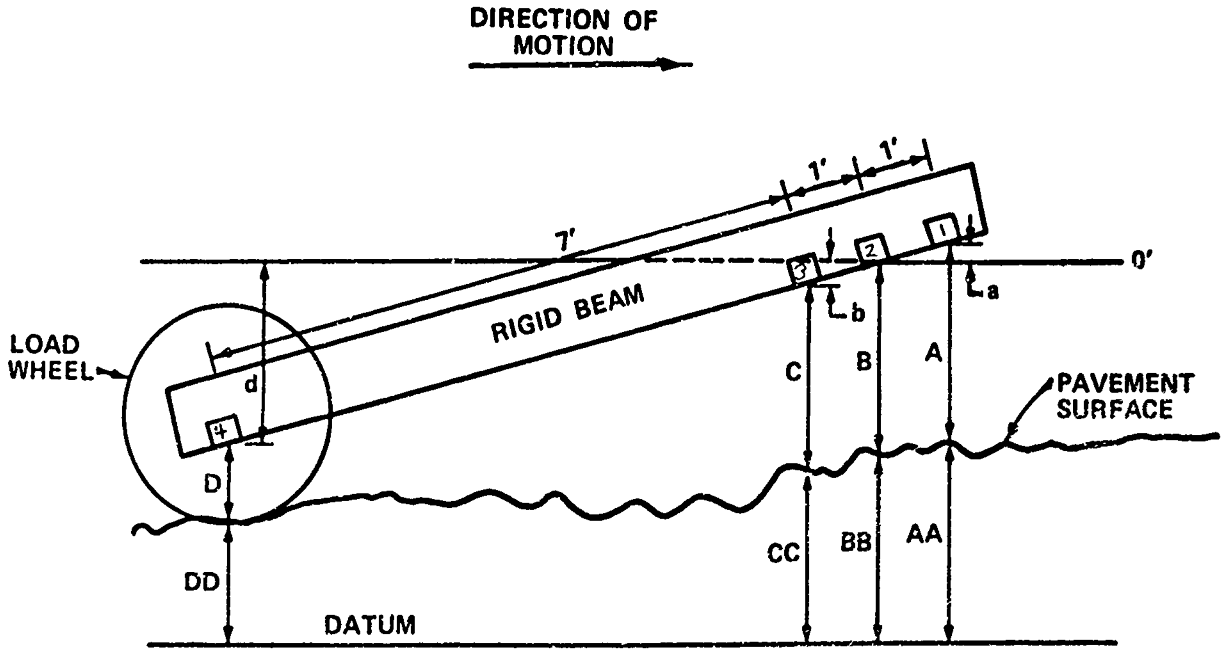


Figure 3. Schematic of profilometer

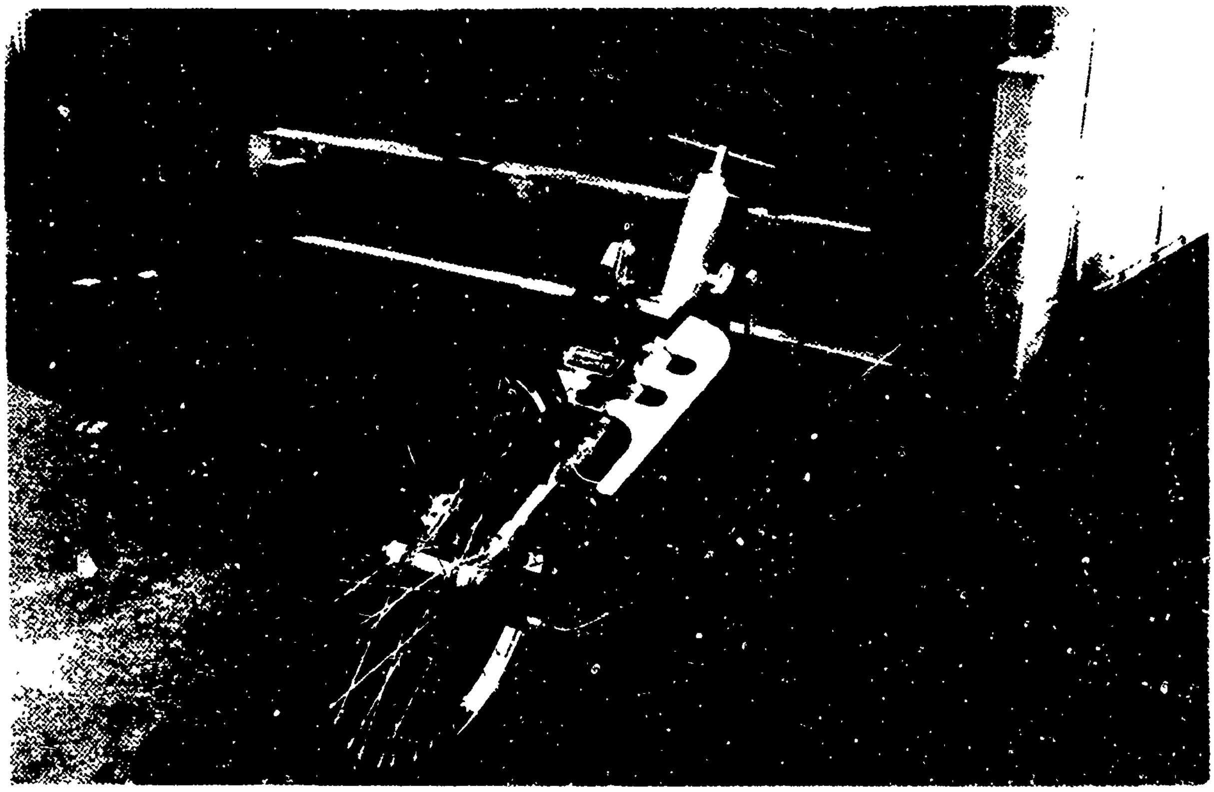


Figure 4. Distance measuring wheel

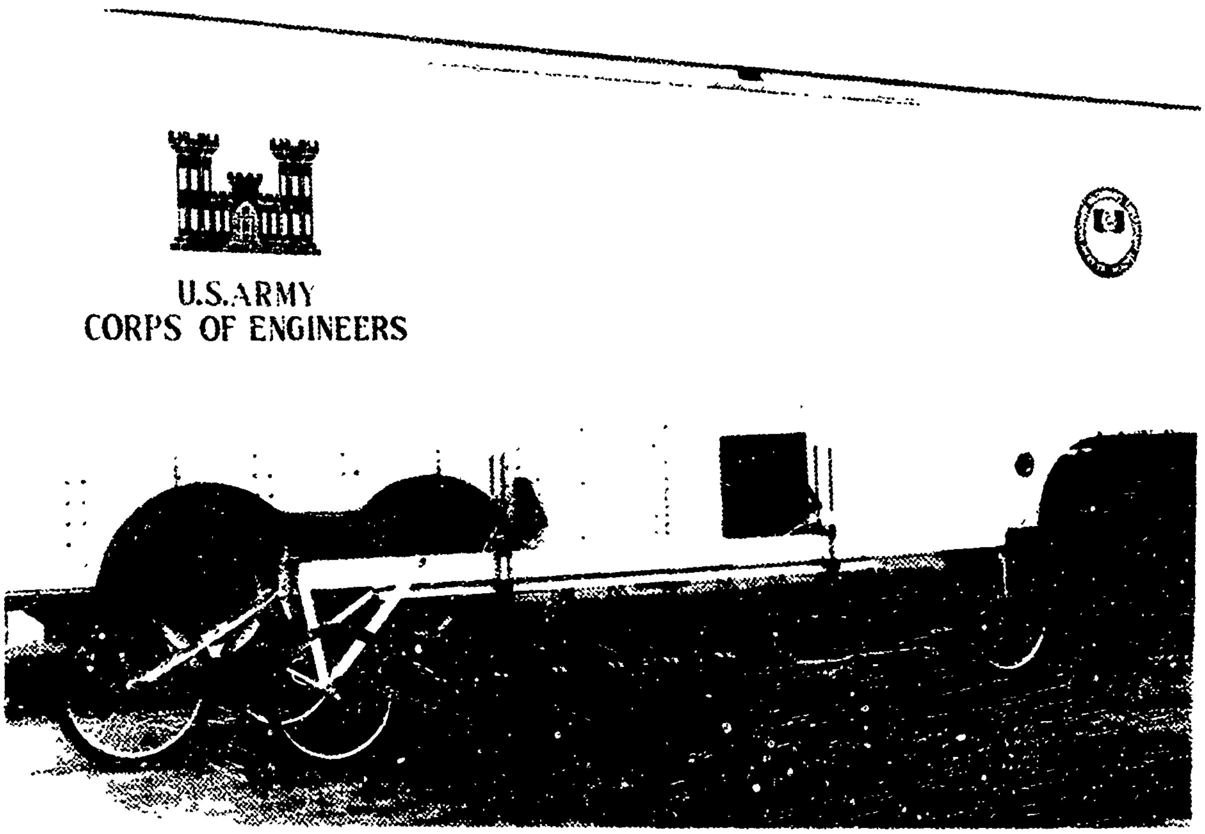


Figure 5. Laser profilometer mounted on cart

MICROCOMPUTER

A Heath-11 microcomputer system was used to acquire and process the data. The Heath-11 is a 16-bit LSI-11/2 microprocessor with 64 kilobytes of memory. A Data Systems Design winchester and floppy disk combination was added to the system to provide greater mass storage and reliability. The winchester disk is a 10-megabyte disk, and the floppy disk is a single-sided, double-density, 8-in. disk supplying 256 kilobytes of removable storage. The floppy disk can also be used in a single-sided IBM 3740 mode. A Heath H-19 CRT terminal is used for program control. Twenty-four 80-character lines can be displayed on this terminal. A TI-810 line printer is used to provide a hard copy of programs and list results. This printer uses standard 14-in. line printer paper and prints at 150 characters per second. Both terminal and line printer were interfaced via RS-232C ports.

The measuring wheel, the lasers, and a set of four toggle switches were also interfaced to the microcomputer via five 16-bit parallel ports.

The system requires 110-volt, 60-Hz AC power. For mobile data acquisition, the system must be shock mounted. The disk system is critical to shock factors.

A diagram of the microcomputer system is shown in Figure 6. The operating system is HT-11. FORTRAN IV and assembly language are used as programming languages.

PROFILOMETER ALGORITHM

Several different algorithms are used to calculate the profile. Their general form is:

$$A = (k + 1) \times B - k \times C - a + (k + 1) \times b - k \times c$$

where:

A = distance from datum to surface

B = previous value of A

C = previous value of B

a = distance from first laser to surface

b = distance from second laser to surface

c = distance from third laser to surface

k = the ratio of the distance between laser 1 and 2 to the distance between laser 2 and 3

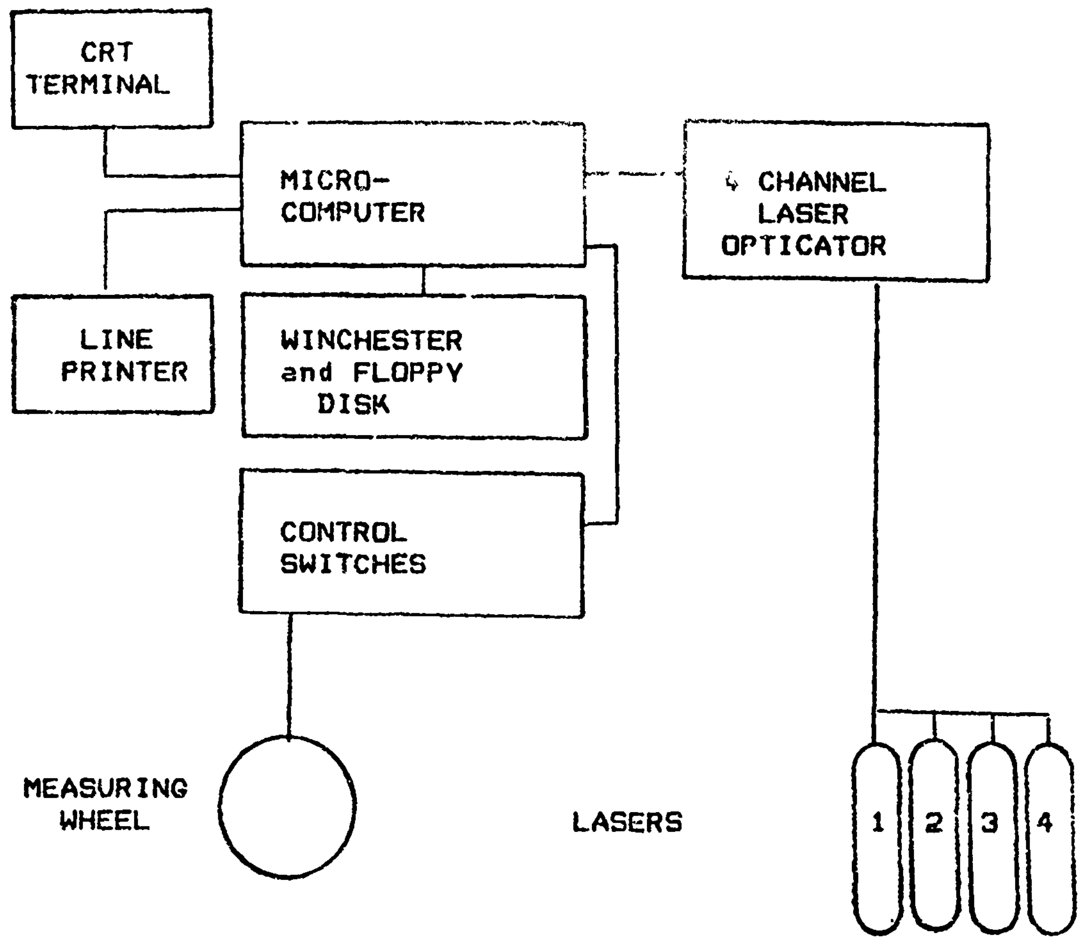


Figure 6. Schematic of microcomputer system

Figure 7 shows the distances used in determining elevations.

A derivation of this algorithm is given in Appendix B.

As the beam moves down, the pavement data is acquired and the average values of a, b, and c are saved for each iteration. An example of the first three iterations of the algorithm is shown in Figure 8. During the first iteration the values of B and C are not known and can be assumed to be the same value. These assumed values determine the depth and slope of the datum. The first A is calculated using the profilometer algorithm; the measured a, b, and c laser readings; and the assumed B and C values. The next values of A can then be calculated using the next average a, b, and c values and the previous A as B and the previous B as C. This recursive algorithm continues in this same manner to the end of the run.

In the test reported herein four lasers were mounted 1 ft apart on the beam. With this configuration the profile can be computed using four combinations of lasers; A-B-C, B-C-D, A-B-D, and A-B-C-D. When lasers A-B-C and B-C-D are used, k will be equal to 1 and the profile algorithm becomes:

$$A = 2 \times B - C - a + 2 \times b - c$$

and

$$B = 2 \times C - D - b + 2 \times c - d$$

When lasers A-B-D are used, k is equal to 0.5 and the profile algorithm becomes:

$$A = 1.5 \times B - 0.5 \times D - a + 1.5 \times b - 0.5 \times d$$

Combining the algorithm for lasers A-B-C and B-C-D, the following formula can be used:

$$A = B + C - D - a + b + c - d$$

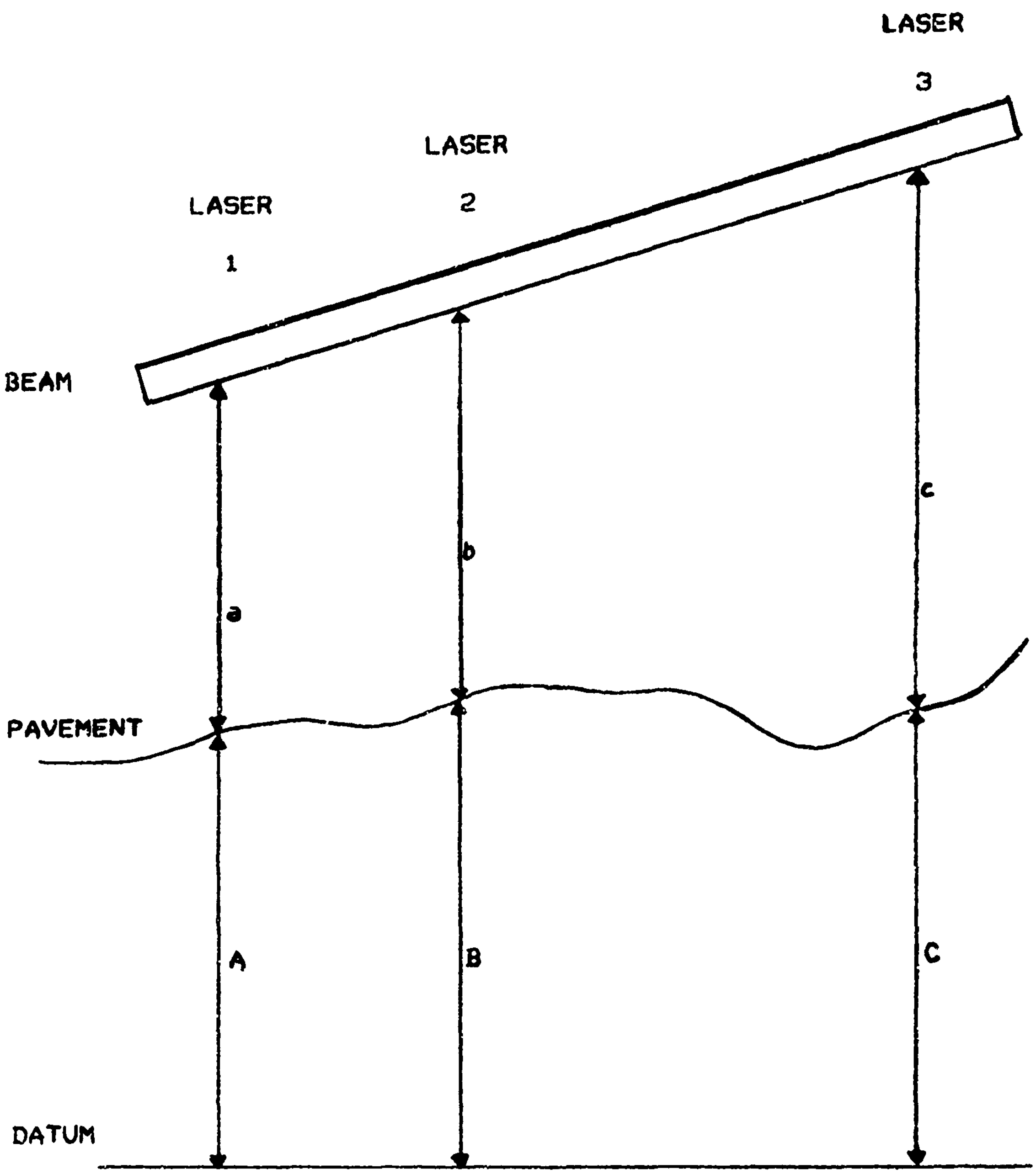


Figure 7. Distances used in determining elevations

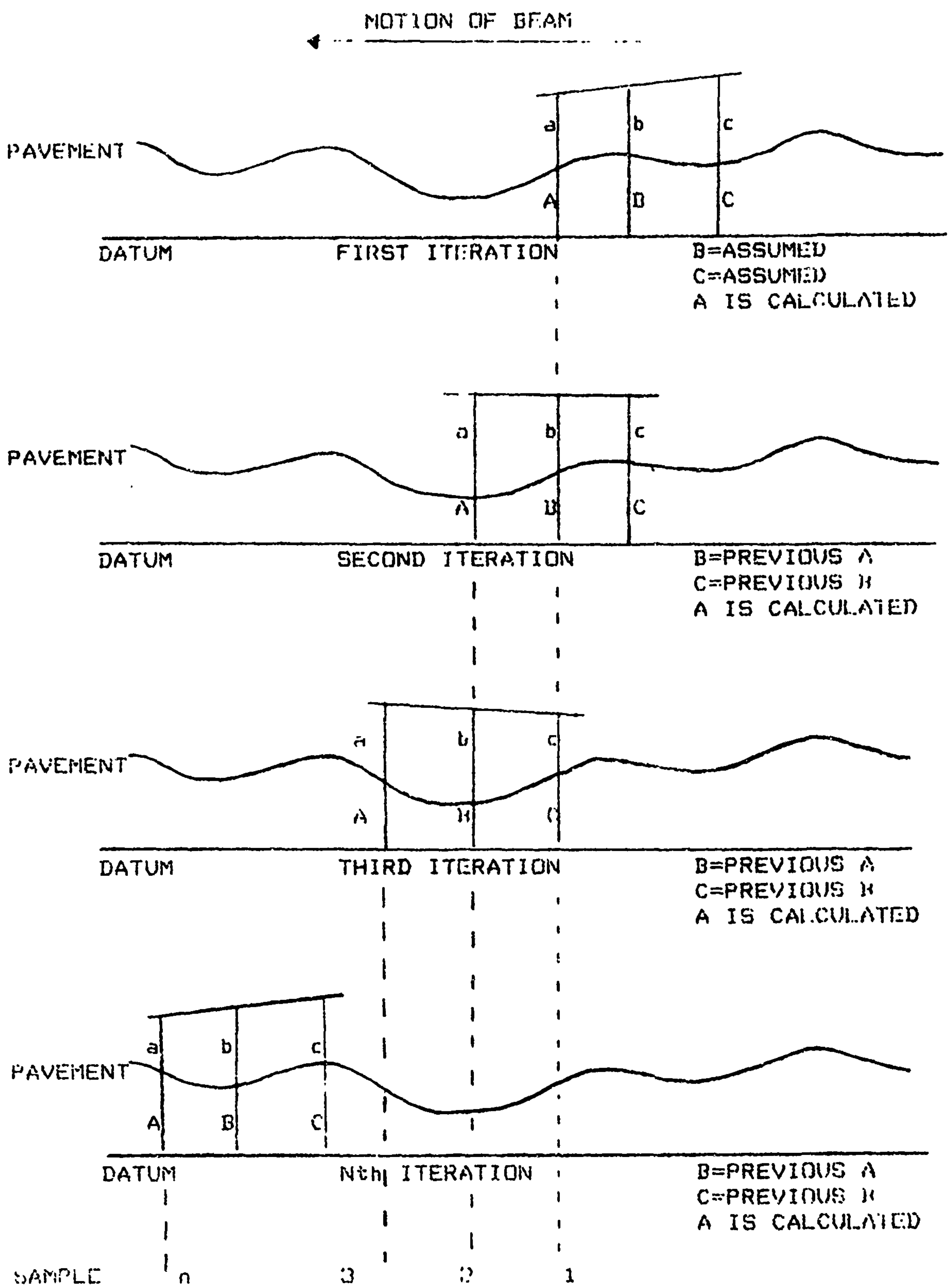


Figure 8. Description of multiple elevation determinations

Profiles were computed using all four methods. The combination of lasers A-C-D does not give valid results because the distance between lasers c and d is not a integer multiple of the distance between a and c.

ACQUISITION SOFTWARE

The acquisition program is written in assembly language to attain the high speed required by this process, and to provide more storage room for the acquisition buffer.

The acquisition software performs the following functions:

a. The program first monitors the start/stop switch until start is turned on.

b. Next the measuring wheel is monitored to determine when the square wave output changes polarity. Each change in polarity represents 2 in. of movement by the measuring wheel. The software counts these polarity changes to indicate when the beginning and end of each sample set has occurred. A sample set can be any length that is an integer multiple of 2 in.

c. Data are then acquired from the lasers and a double precision 32-bit integer sum of the samples of each laser is calculated. A counter of the number of samples is also incremented with each valid sample taken. The measuring wheel is continuously monitored after each sample to determine the end of a sample set.

d. The average of each sample set is calculated for each of the four lasers. These averages are stored in the acquisition buffer.

e. At the end of each sample set a list switch is monitored. If this switch is on, the average value of the four lasers and the count of valid readings are printed at the CRT terminal.

f. The software then checks the start/stop switch. If the start switch is on, more data acquisition continues. If the start switch is off, the data stored in the acquisition buffer is written to disks and the acquisition program is exited.

The acquisition buffer memory is 20,000 16-bit words. A maximum of 5000 sample set averages for four lasers can be stored before dumping to the disk. A flow of the acquisition program is shown in Figure 9.

PROCESSING SOFTWARE

The processing program is written in FORTRAN. Several overlays of programs are used to execute the following functions:

a. The processing program writes the raw data to a new file so the data acquisition can continue and the processing can be done later.

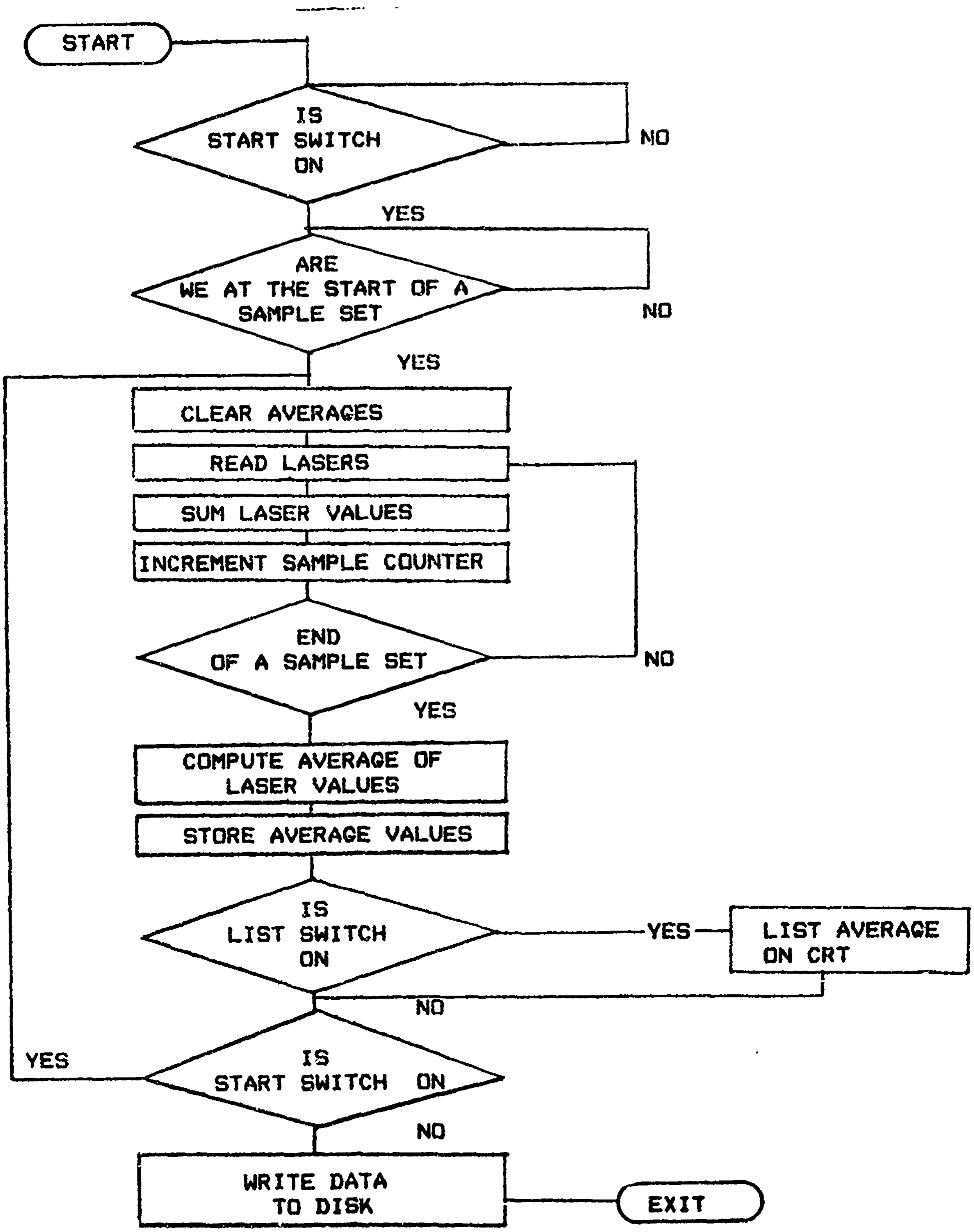


Figure 9. Flow diagram of acquisition program

b. When all data acquisition is complete, the processing program reads the data and adjusts the laser values to correct for any nonlinearity in the mounting of the lasers on the beam. It is shown in Appendix C that the first derivative of the profile with respect to distance is Σ (-a + 2b - c + e) where e is the error and a , b , and c are the laser readings. For long profiles this derivative should be near zero. The processing program calculates the value of e with the formula:

$$e = -(1/N) \Sigma (-a + 2b - c)$$

The laser readings are then modified such that Σ (-a + 2b - c) = 0. These correction values are listed for each profile for comparison.

c. The next process is to run the corrected laser data through the profile computation algorithm for each of the combinations of lasers used. The profile data are written to another disk file for further processing and plotting.

d. At this point three known elevation values of the profile are input into the system. The starting, ending, and center points are best. The second-degree curve that defines the difference between the measured profile and the known profile is calculated. This curve shows the trend of the error in the profile. Next the correction curve is evaluated at every point of the profile and subtracted from the measured profile. This procedure removes much of the error from the profile. The adjusted profile is then listed and plotted.

e. After all the desired testing and plotting is completed, data can be copied onto an 8-in. floppy disk so additional analysis and plotting can be done on other computers.

A flow diagram is shown in Figure 10.

ADDITIONAL SOFTWARE

Additional software was written to provide ways of reducing the error in the measured profiles. Programs were written to reduce errors in the following ways:

a. Data was processed both forward and backward and then averaged to give better results.

b. Profiles were calculated and error was removed from these profiles by taking six known samples from the rod and level survey and using a least-mean-square fit of these samples to calculate a curve that could be used to correct the profilometers' profile. This was done on the longer profiles that showed large error buildups.

c. Several adjacent sample sets were averaged to improve representative samples.

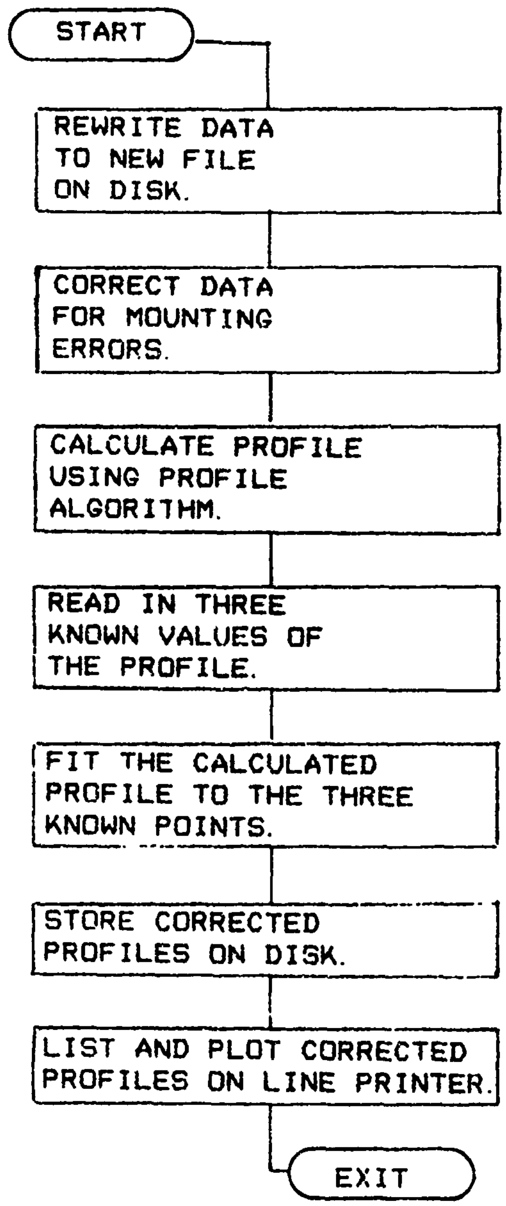


Figure 10. Flow diagram of processing software

d. Profiles were filtered with a recursive high-pass filter to remove wavelengths greater than 30 ft. These filtered profiles were plotted and compared with other test of the same profile.

TEST RESULTS

TEST DESCRIPTION

To evaluate the laser profiling system, data were collected over previously surveyed profiles. Only the undeflected profiles were measured.

Tests were conducted at two locations. One set of tests was conducted on a presurveyed 500-ft asphalt segment of St. Lawrence road at the Waterways Experiment Station. The other set of tests was conducted on a concrete runway at Tyndall Air Force Base, Fla. Rod and level profiles of both test areas are presented in Figures 11 and 12.

At the Waterways Experiment Station test area, the rod and level survey was measured at intervals of 1 ft. The road had an asphalt surface and contained an 8-ft change in elevation. These tests were run with both the three-wheel cart and the 18-wheel tractor-trailer rig. Data were acquired at intervals of 1 ft with the lasers spaced at 1-ft intervals. Tests were run in both east and west directions.

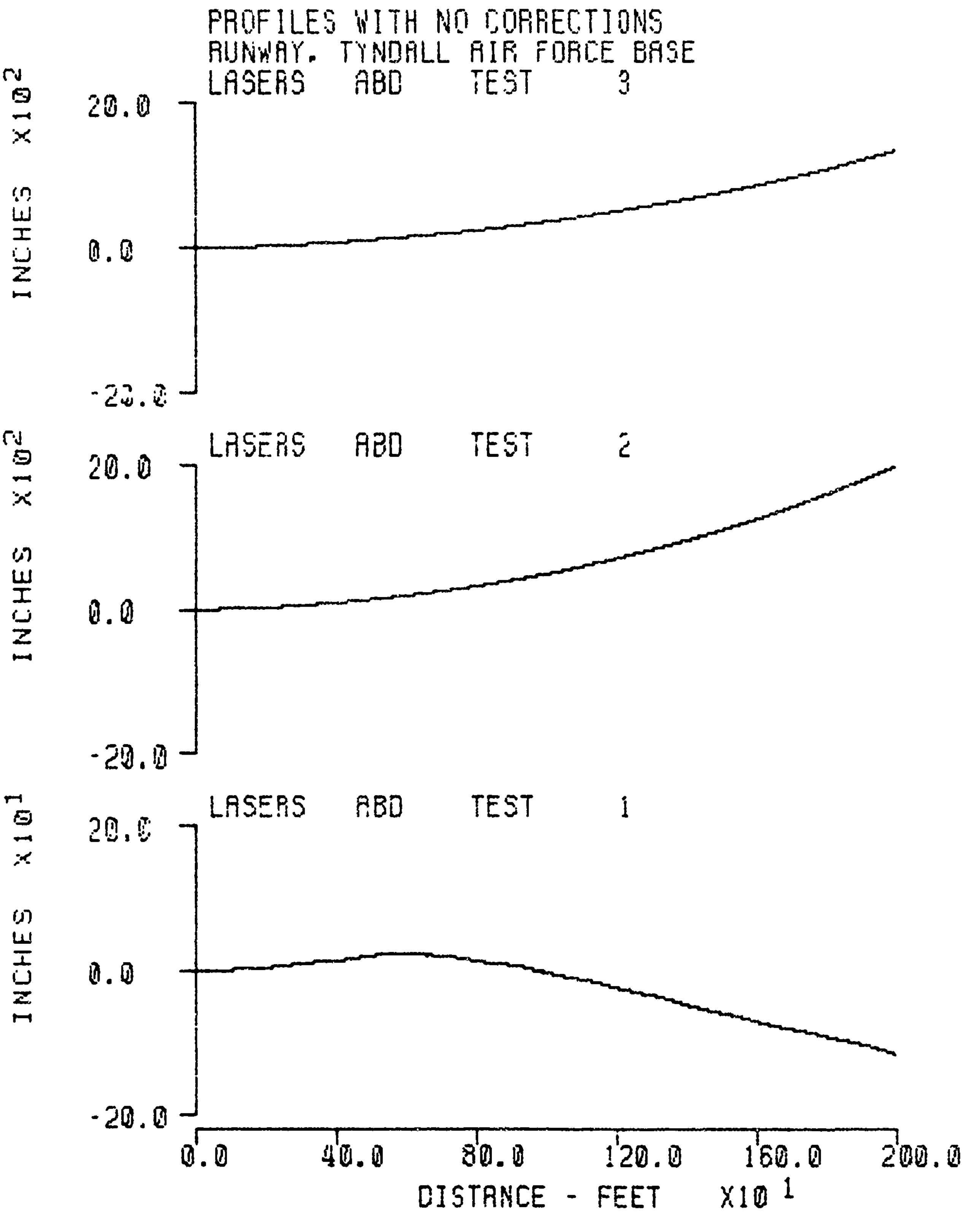
For the tests conducted at Tyndall Air Force Base, the same laser spacing was used; however, tests were conducted in only one direction at Tyndall.

During these tests the speed was maintained at approximately 5 mph. Two hundred to six hundred samples per foot were taken during each sample set. Each sample acquired by the computer was the average of eight samples that were averaged by the laser opticator. A rod and level survey was made of both pavements for comparison.

Deflected profiles near a loaded wheel should not be attempted until unloaded profiles can be measured with an error of less magnitude than the deflection caused by a loaded wheel.

ERRORS

As can be seen from the generalized form of the algorithm, each iteration is a function of some previous calculation. The first two values that are assumed determine the slope of the datum from which the profiles heights are to be measured. For convenience these first values are chosen to be the same value. Correction for this error is done by the processing program when the known starting and stopping points are given. Because each point is derived from prior measurements, error introduced by the system increases with each additional step. If these errors are not corrected,



PROFILES WITH NO CORRECTIONS
RUNWAY. TYNDALL AIR FORCE BASE
LASERS ABD TEST 3
INCHES X10 2
20.0
0.0
-20.0
LASERS ABD TEST 2
INCHES X10 2
20.0
0.0
-20.0
LASERS ABD TEST 1
INCHES X10 1
20.0
0.0
-20.0
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE - FEET X10 1

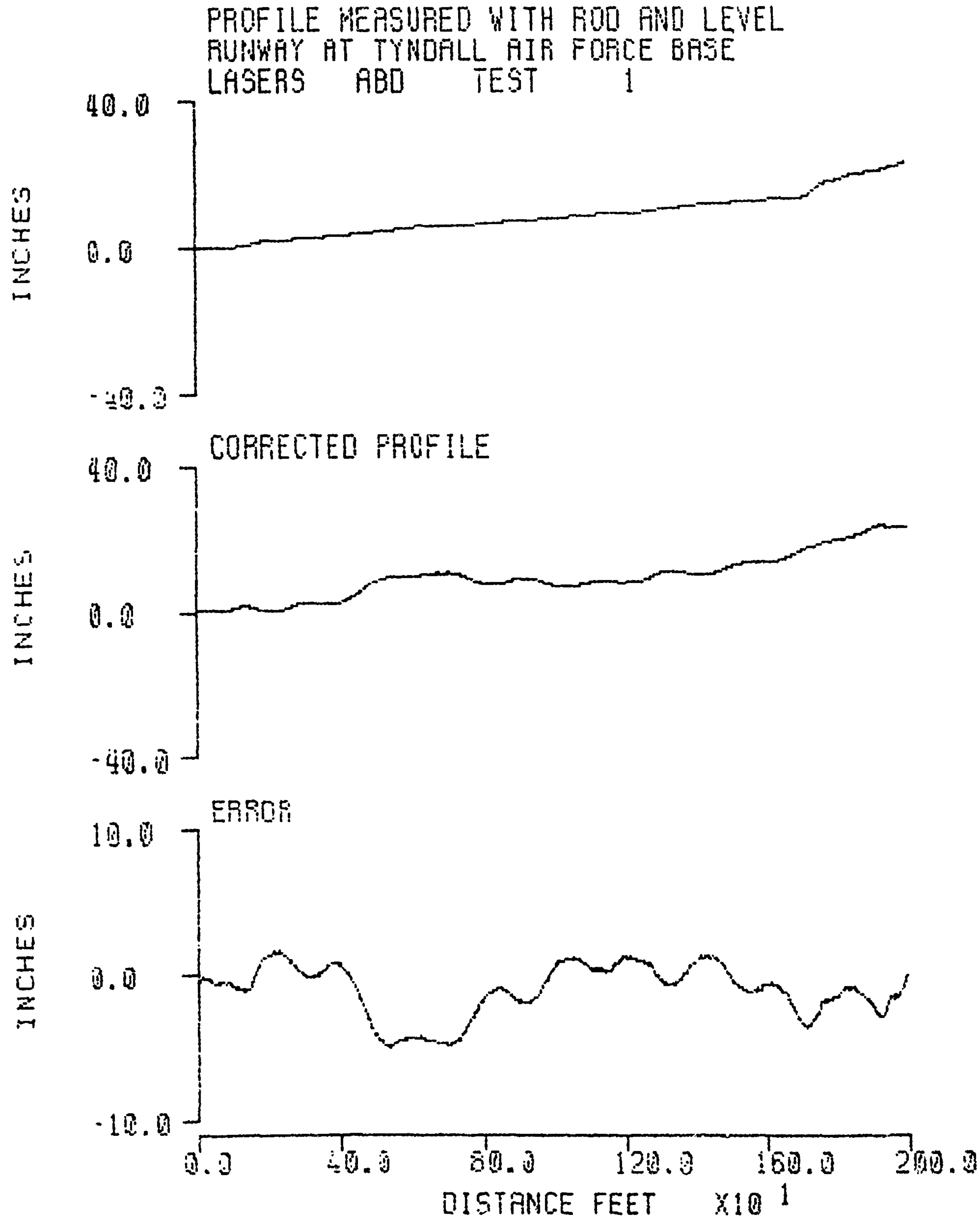


Figure 12. Typical profile measured on concrete pavement

profiles become grossly inaccurate. The equation for the error caused by a constant error in one of the lasers can be shown to be:

$$\text{Total error} = \text{Error} \times 0.5 \times \text{Iteration} \times (\text{Iteration} + 1)$$

The derivation of this error formula is given in Appendix C.

When considering only the error caused by the resolution of the lasers, this buildup error is substantial. For a 2000-ft profile sampled at 1-ft intervals the resultant error can be calculated as follows:

$$\text{Total error} = 0.001261 \times 0.5 \times 2000 \times (2000 + 1)$$

$$\text{Total error} = 2521.6 \text{ in.}$$

Also consider the error at the loaded end of a 9-ft beam after only 9 ft:

$$\text{Total error} = 0.001261 \times 0.5 \times 9 \times (9 + 1)$$

$$\text{Total error} = 0.0567 \text{ in.}$$

One way of reducing this error is to use the lasers in an asymmetric configuration. This benefit can be seen from the generalized form of the profile algorithm. As the distance between lasers b and c increases, the ratio k becomes smaller. As k becomes smaller, the effect of the previous values, B and C, is reduced.

There are several sources of errors. One source results from the lasers not being in a straight line. This is always the case because it is practically impossible to align the lasers in the vertical plane within the accuracy of the laser (0.00126 in.). The processing program can correct for this error. However, the accuracy of this correction is also dependent on the data collected. Additional error occurs when the lasers do not collect the same sample set as they move over the same section of the road. This error can be due to the beam not moving in a straight line (crab walking) or pot holes in the road. It can also be due to the truck moving at a nonconstant speed. Another source of error is the accuracy of the lasers.

The measuring wheel is yet another source of error. The wheel has an accuracy of 1 percent. When the pavement is flat, the accuracy of the measuring wheel will cause a random error that should not cause a great error in the profiles. When the pavement is on a hill, the error is more substantial. In this case the error will be a function of the slope of the hill and the error of the measuring wheel.

COMPARISONS OF PROFILES

The first values compared are those of delta b and delta c of one run to the values of each of the other runs. Delta b and delta c are the values the processing program had to add to lasers b or c to make their sums define a straight line. This correction is made to correct for any misalignment of the lasers in the vertical plane. Ideally these delta b and delta c values should be equal to all other delta b and delta c values provided no bending occurred in the beam. The amount these values vary from one run to another indicates that there are other sources of error affecting the quality of the recorded data. Table 2 lists delta b , delta c , and length of test.

Comparison were also made among all the tests using both A-B-C and B-C-D to compute the profile. Ideally both of these should give identical results. The failure of these two profiles to give similar results could indicate that errors are due to a laser being miscalibrated, the lasers crab walking, or any problem causing the lasers not to trace the same sample set. Selected plots of these profiles are shown in Appendix A.

Comparisons were also made among configurations A-B-C, B-C-D, A-B-C-D, and A-B-D. These results compare the use of four lasers to three lasers and compare asymmetric to symmetric configurations. Plots of the profiles are also shown in Appendix A.

In addition, comparisons were made between these computed results and the known profiles. These known profiles were made with a rod and level within a month of the date of the profilometer test. Plots of both tests and their deviations from the known profiles are shown in Appendix D. Plots of the test which show the least error are shown in Figures 11 and 12. These plots show the approximate amount of error in the profiles after corrections have been made.

Comparisons were also made between the high-pass filtered data of different test of the same profile. These plots indicate how well the profilometer can be used for small wavelength profiles. The root-mean-square (rms) values of these filtered profiles are listed in Table 3. Plots of these tests are shown in Appendix A.

Comparisons were also made between profiles run in forward and reverse directions and between data processed in forward and reverse directions. No substantial difference was shown.

Profiles using 1-ft samples for a sample set were compared to those using larger sample sets of 3 to 5 ft. There was no substantial difference between these profiles. Therefore the 200 to 600 samples taken in a 1-ft sample set give a very representative sample.

EVALUATION OF INSTRUMENTATION

Individual components used in testing are evaluated as follows:

a. The lasers were accurate to manufacturer's specification. They are durable and well suited for field use.

b. The sealed winchester disk provided a much more reliable storage media than did the floppy disk. Originally the system was equipped with only the floppy disk. The floppy disk were unreliable in field conditions, and considerable time was lost due to breakdown of the disk unit.

c. The microcomputer, terminals, and printer performed well under field conditions and were adequate for this project.

d. The measuring wheel functioned well electrically, but mechanically does not have the desired accuracy. Distances measured by the measuring wheel for the 500- and 2000-ft test are shown in Table 2.

Table 3. Comparisons of Rms Values of High-Pass Filtered Profiles

Test	Rms, in.	Location
1	0.03668	Tyndall
2	0.03893	Tyndall
3	0.03852	Tyndall
4	0.11252	WES
5	0.11233	WES
6	0.11569	WES

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Three categories should be considered when studying the performance of the profilometer. These categories are: loaded profiles, short wavelength profiles, and long wavelength profiles.

It is unlikely that loaded profiles can be measured with the existing system. By mounting the load-measuring laser 9 ft from the first profile-measuring laser the system has an error of at least 0.0567 in.

Short wavelength profiles can be measured more accurately than long wavelength profiles with this profilometer. In a smaller wavelength profile the cumulative error buildup will be less. To reduce the error in the profile, the long wavelengths must be removed. One method is to measure or assume several points on the profile. This known profile is fit to the measured profile to produce the final plot. A digital high-pass filter could also be used. Both methods have some disadvantages. Filtering the data modifies all of the profile to some degree. Measuring points on the pavement with rod and level reduces efficiency and speed of data acquisition.

Measurement of long profiles is not acceptable with this system. The buildup error for long profiles is many times greater than the elevation relief in the profile. This error can be reduced if the number of iterations per profile is reduced. If the lasers are placed 3 ft instead of 1 ft apart, the error will be reduced by a factor of 9.

The present configuration of lasers will not produce the accuracy required for measuring a loaded profile. If separating the lasers by a distance of 3 ft would produce the desired accuracy, the beam would be too long since the measurement of the unloaded profile would have to be outside the deflection basin caused by the loaded wheel (greater than 7 ft).

These conclusions are based on the total system including algorithm, lasers, microcomputer, and measuring wheel.

RECOMMENDATIONS

Based on the finding of this study, the following recommendations are presented:

a. The use of an inertial device (accelerometer) to determine the position of the beam with respect to a datum to reduce the error in the recursive algorithm should be evaluated.

b. A system with lasers separated a minimum of 3 ft should be evaluated.

c. A measuring wheel device should be selected that gives measurements accurate to at least 0.1 percent of the measured length.

d. The use of ultrasonic sensors in combination with lasers to reduce the overall cost of the system and increase redundancy should be evaluated.

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1. Boyth, R. E., "Predicting Pavement Performance Using Time-Dependent Transfer Functions," Joint Highway Research Project, Purdue University and Indiana State Highway Commission, No. 32, September 1972.

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3. White, T. D., Measured Pavement Response to Transient Aircraft Loadings, Ph. D. thesis, Purdue University, May 1981.

4. Highter, W. H., and Harr, M. E., "Cumulative Deflection and Pavement Performance," American Society of Civil Engineers Transportation Journal, Vol 101, No. TE3, Aug 1975.

5. Harr, M. E., and Ng-A-Qui, N., Noncontact Nondestructive Determination of Pavement Deflection under Moving Loads, Report No. FAA-RO-77-127, Federal Aviation Administration, Aug 1977.

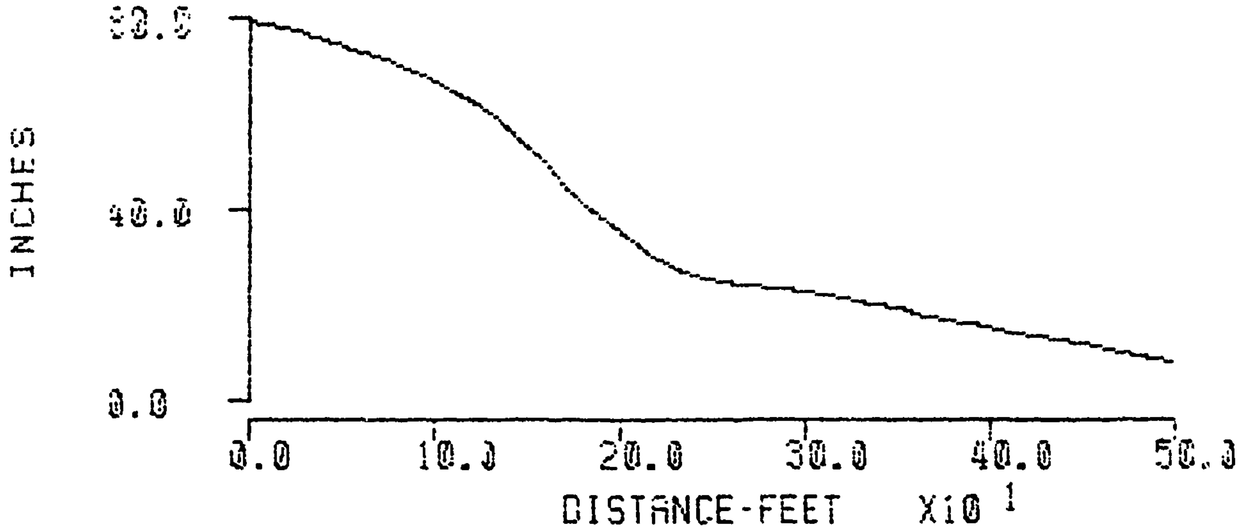
6. Elton, D. J., Noncontact, Nondestructive Pavement Evaluation, Ph. D. thesis, Purdue University, August 1982.

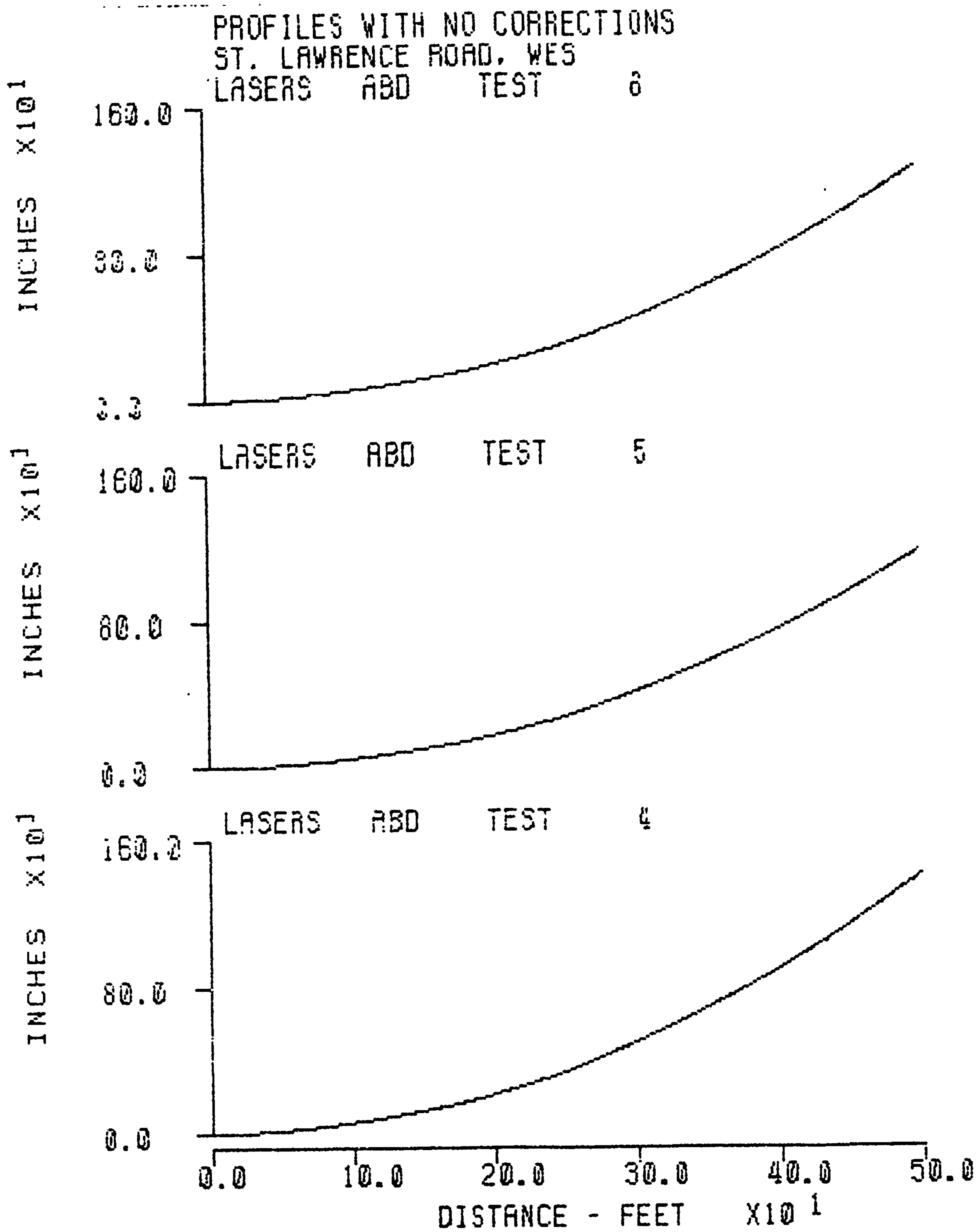
7. Still, P. B., and Jordon, P. G., Evaluation of TRRL High-Speed Profilometer, Transportation Road Research Laboratory Report 922, Crowthorne, Great Britain, 1980.

APPENDIX A

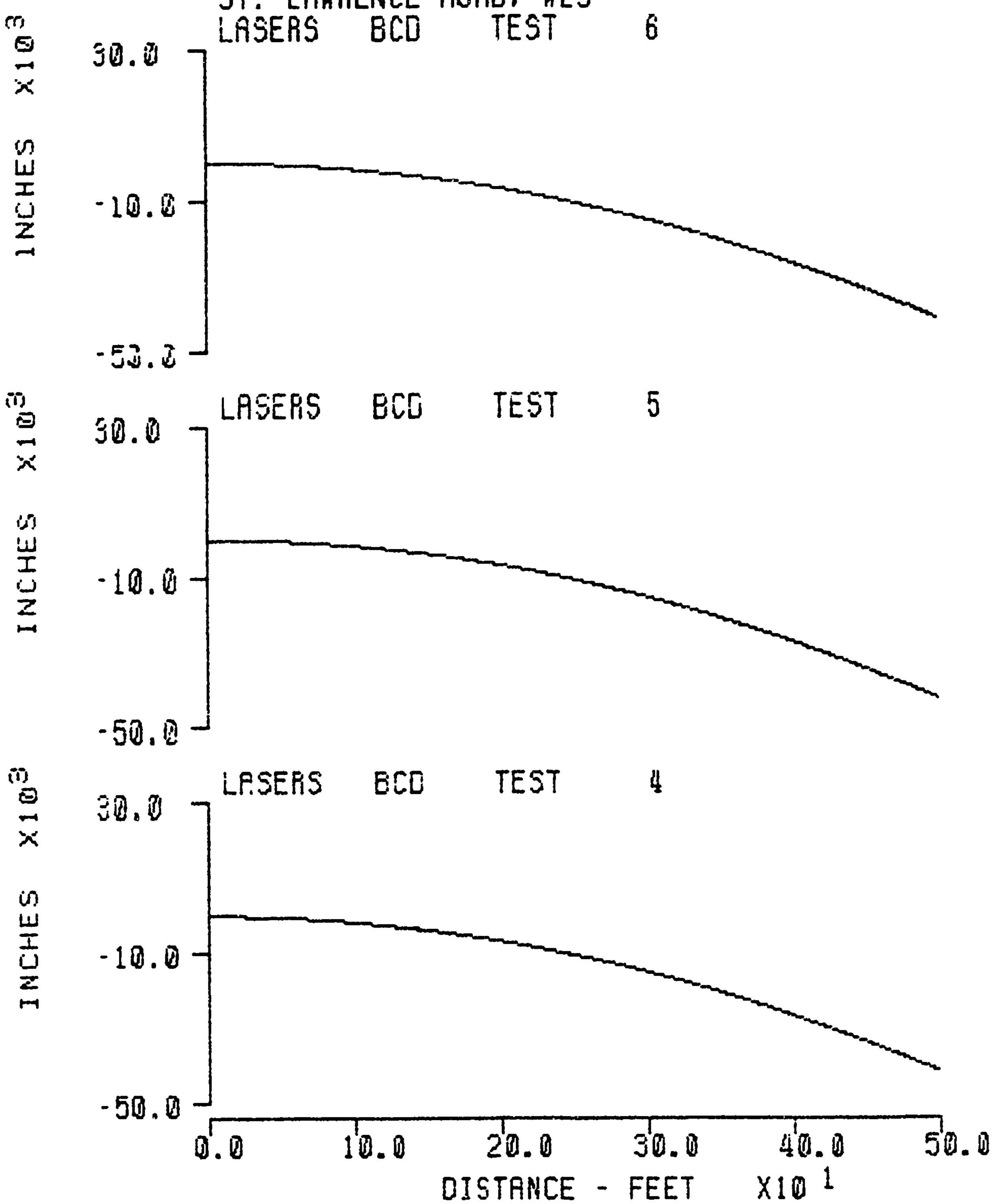
PLOTS OF PROFILES

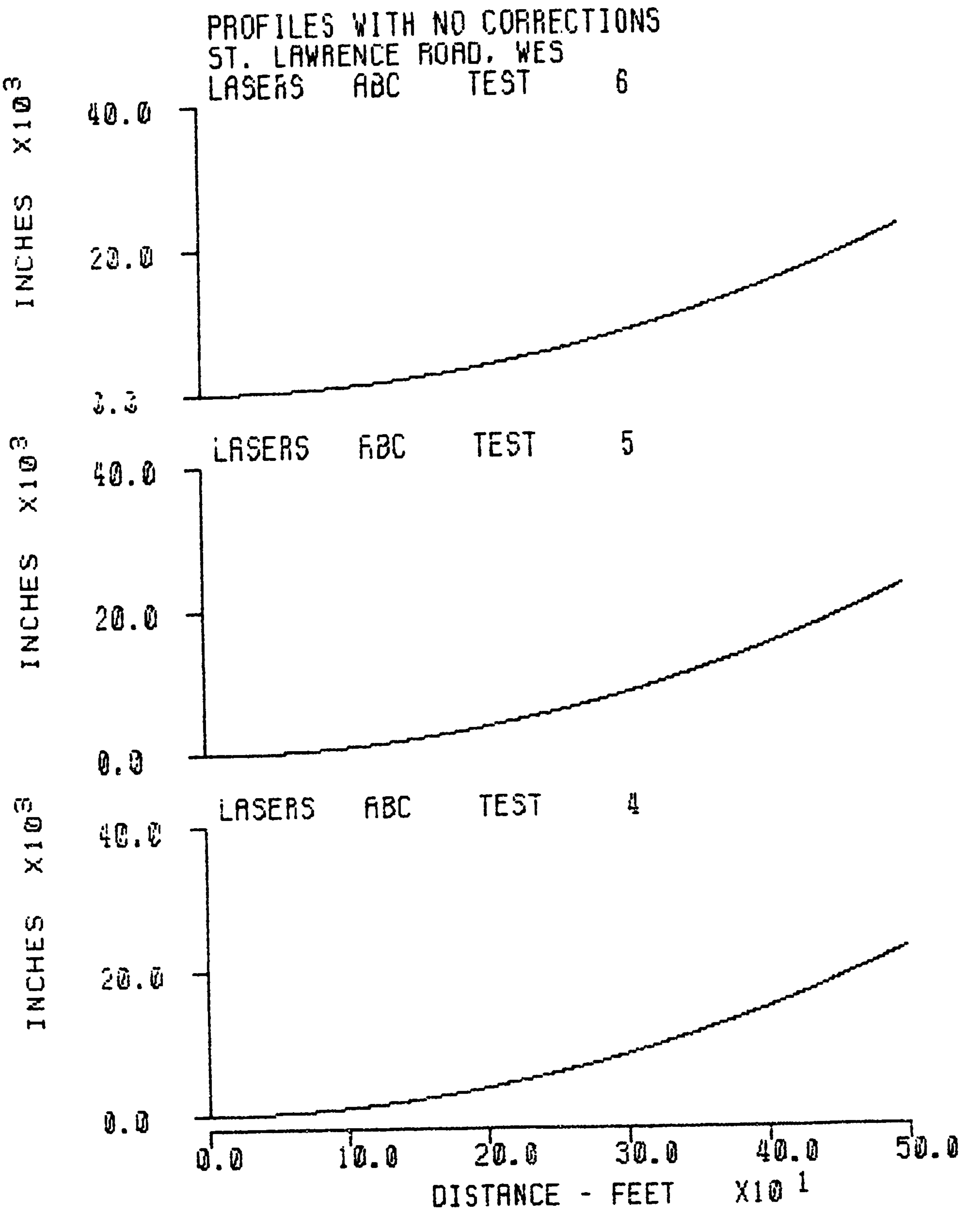
ST LAWRENCE ROAD, WES
PROFILE FROM ROD AND LEVEL SURVEY

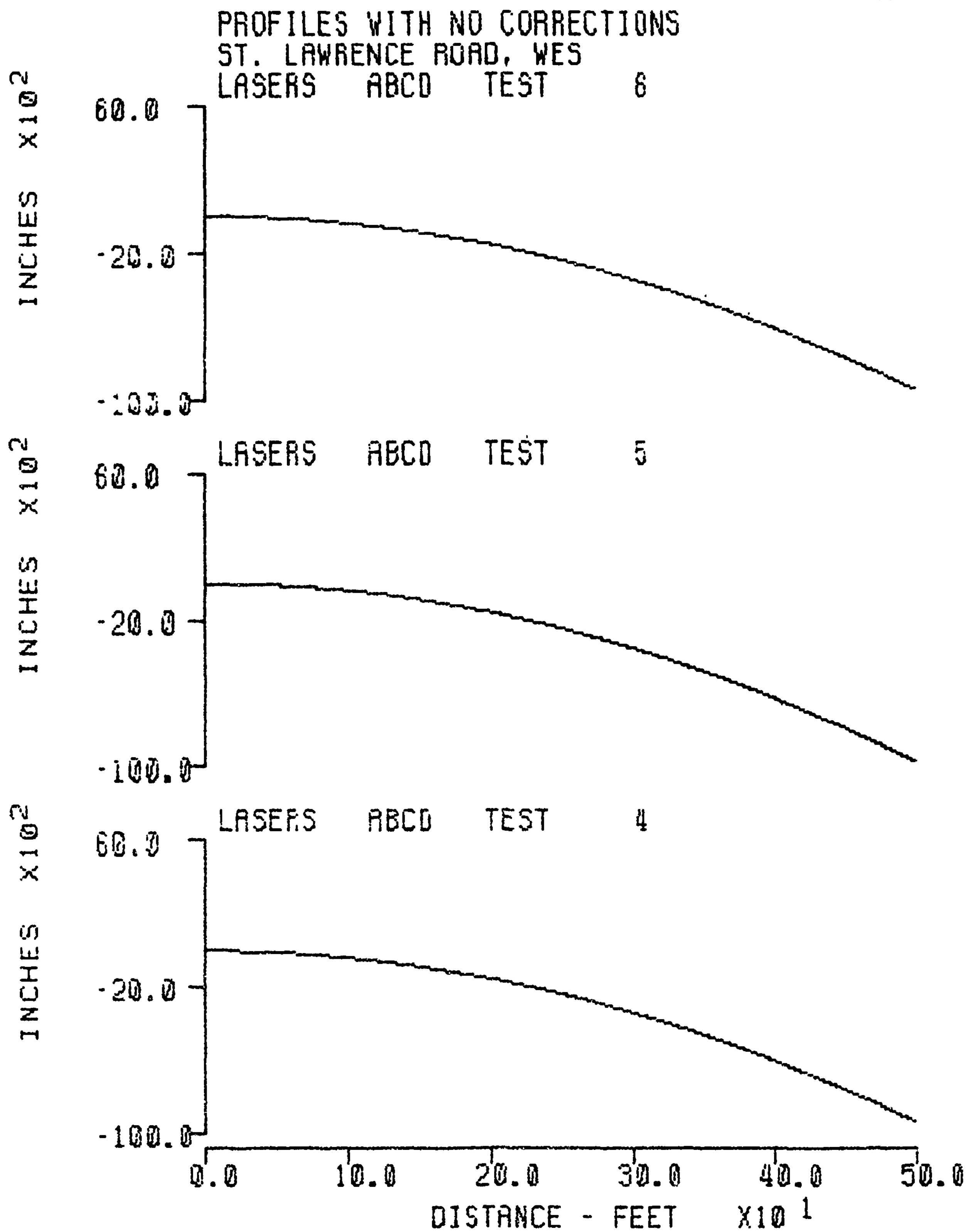


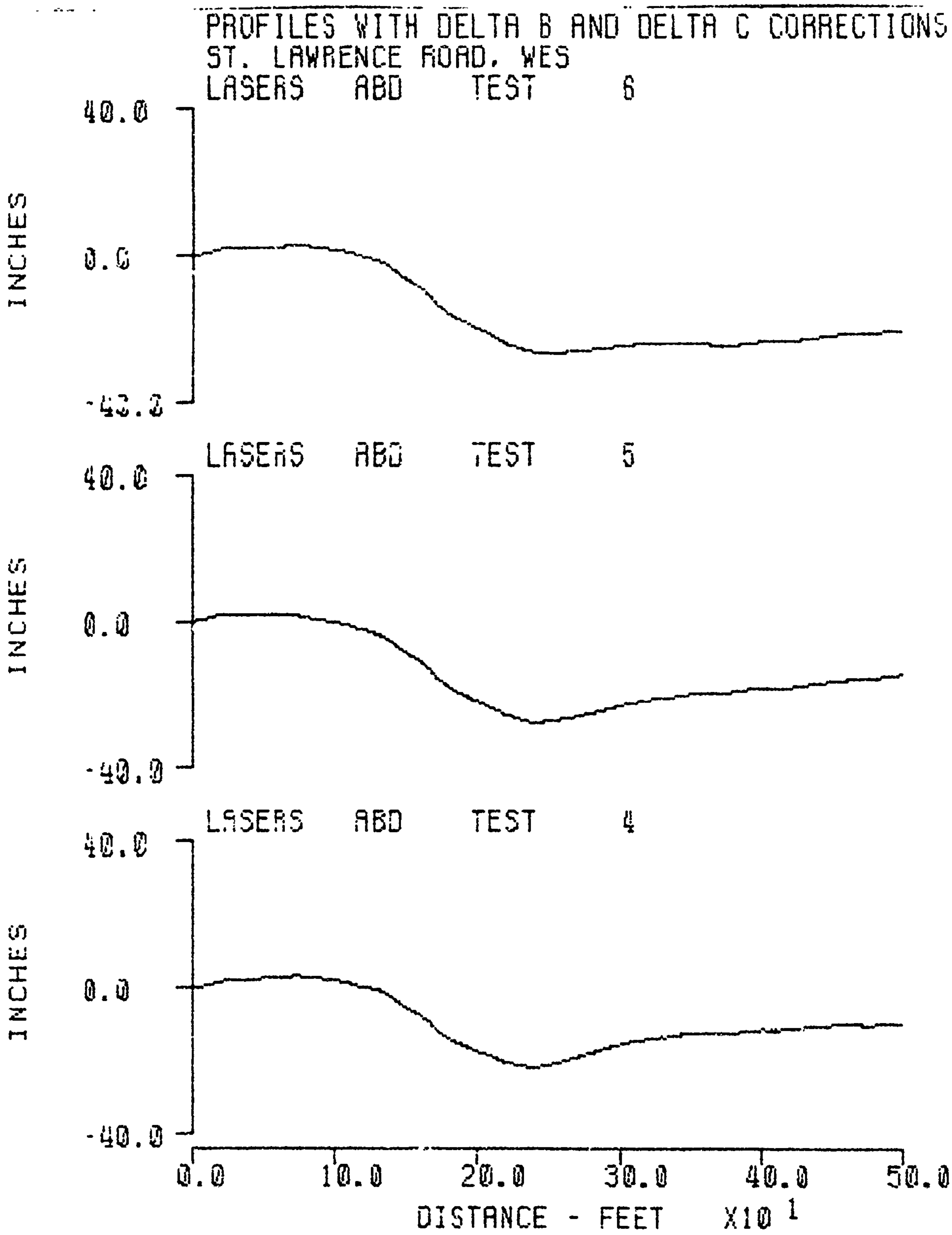

PROFILES WITH NO CORRECTIONS
ST. LAWRENCE ROAD, WES
LASERS ABD TEST 6
LASERS ABD TEST 5
LASERS ABD TEST 4
INCHES X10¹
160.0
80.0
0.0
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE - FEET X10 1

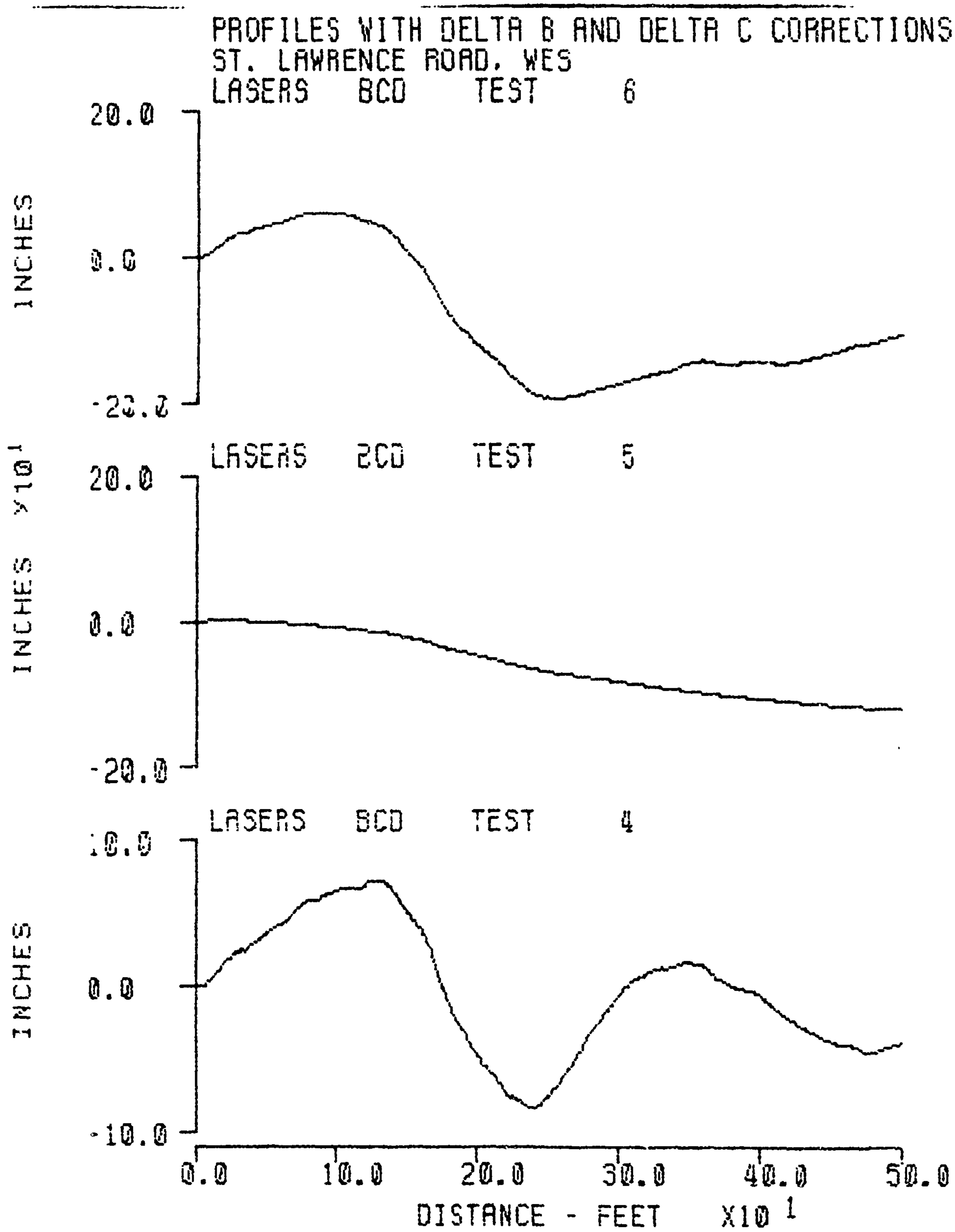
PROFILES WITH NO CORRECTIONS
ST. LAWRENCE ROAD, WES

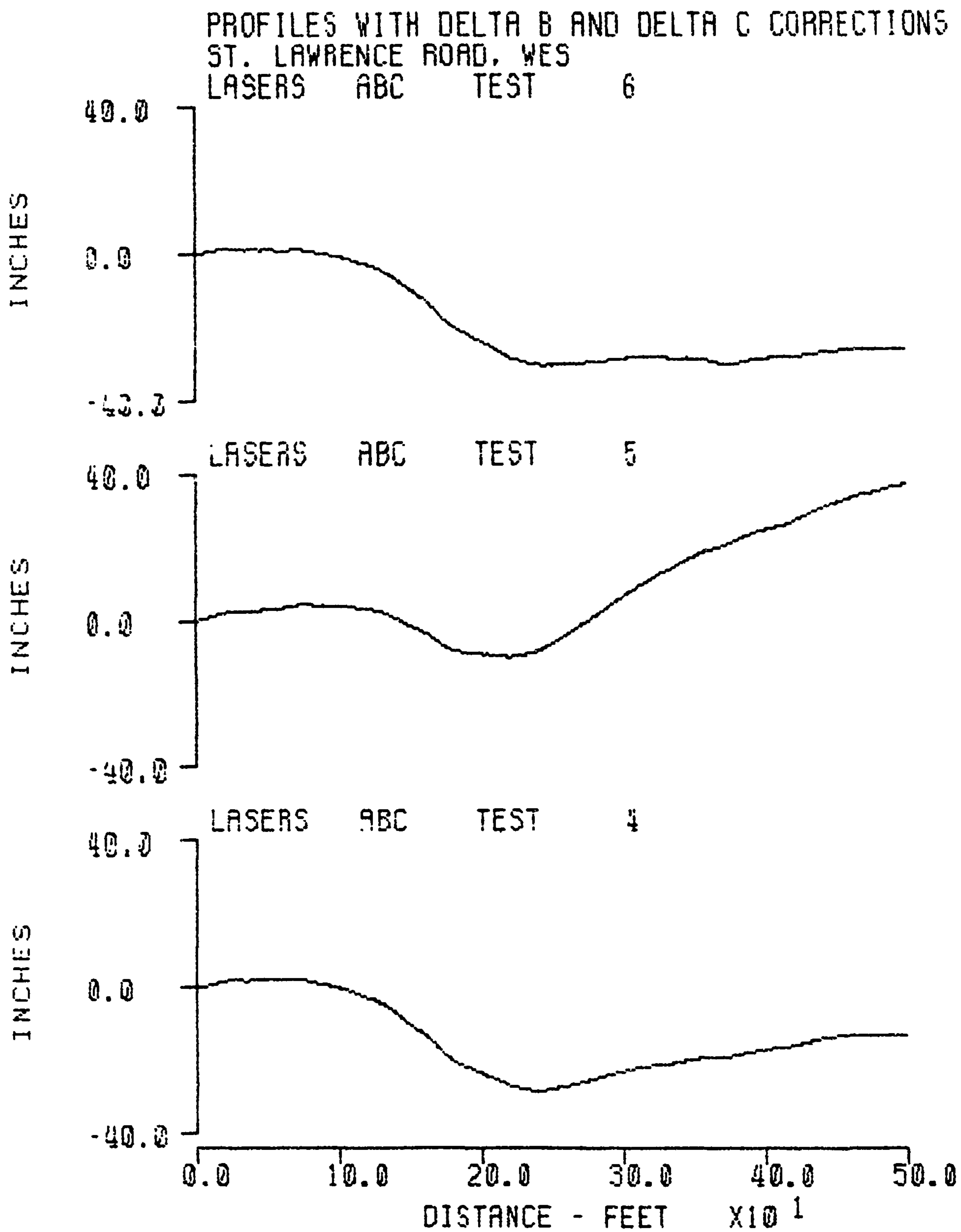


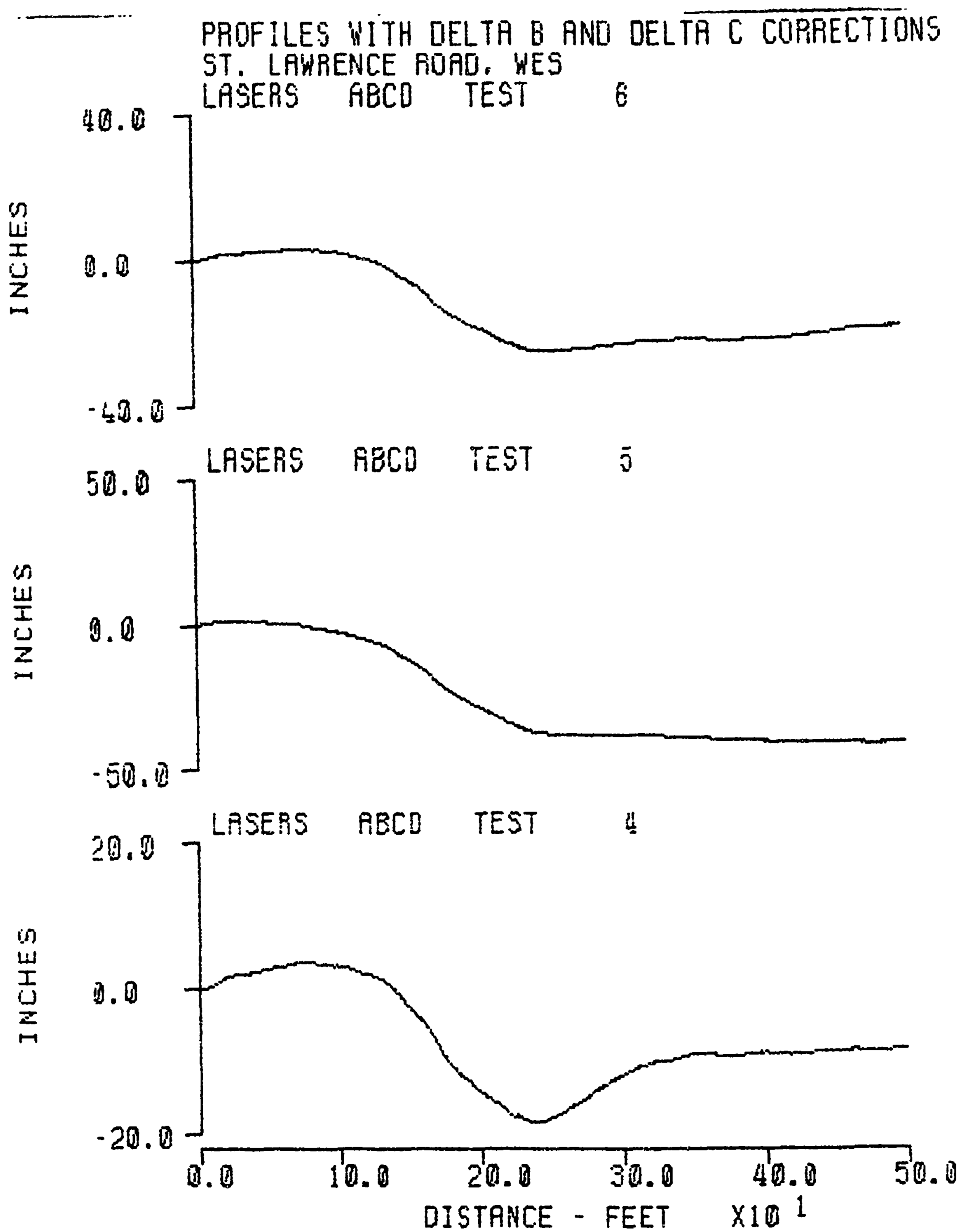

PROFILES WITH NO CORRECTIONS
ST. LAWRENCE ROAD, WES
LASERS ABC TEST 6
INCHES X10³
40.0
20.0
0.0
LASERS ABC TEST 5
INCHES X10³
40.0
20.0
0.0
LASERS ABC TEST 4
INCHES X10³
40.0
20.0
0.0
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE - FEET X10¹


PROFILES WITH NO CORRECTIONS
ST. LAWRENCE ROAD, WES
LASERS ABCD TEST 6
LASERS ABCD TEST 5
LASERS ABCD TEST 4
INCHES X10 2
60.0
-20.0
-100.0
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE - FEET X10 1

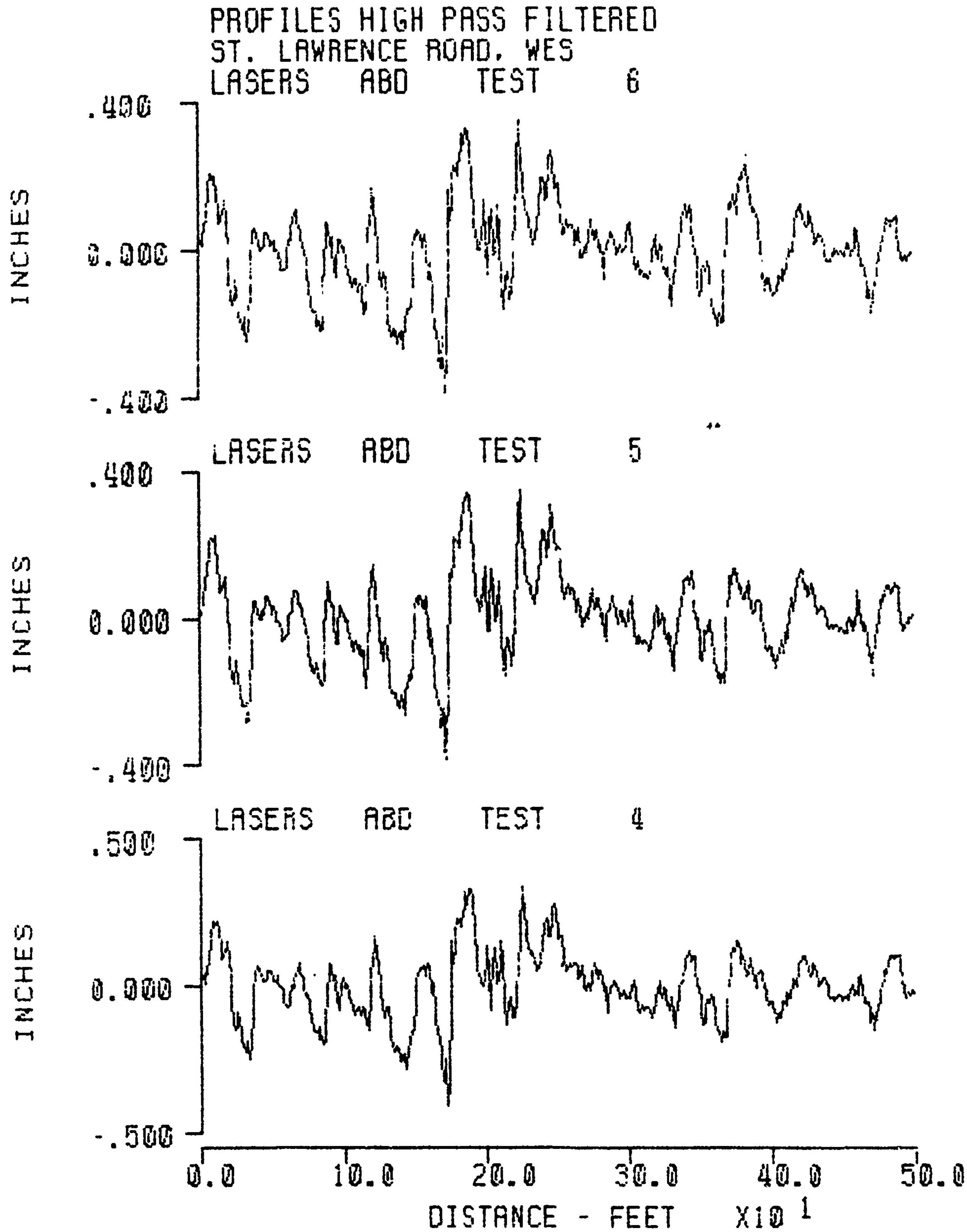

PROFILES WITH DELTA B AND DELTA C CORRECTIONS
ST. LAWRENCE ROAD, WES
LASERS ABD TEST 6
40.0
0.0
INCHES
LASERS ABD TEST 5
40.0
0.0
-40.0
INCHES
LASERS ABD TEST 4
40.0
0.0
-40.0
INCHES
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE - FEET X10 1

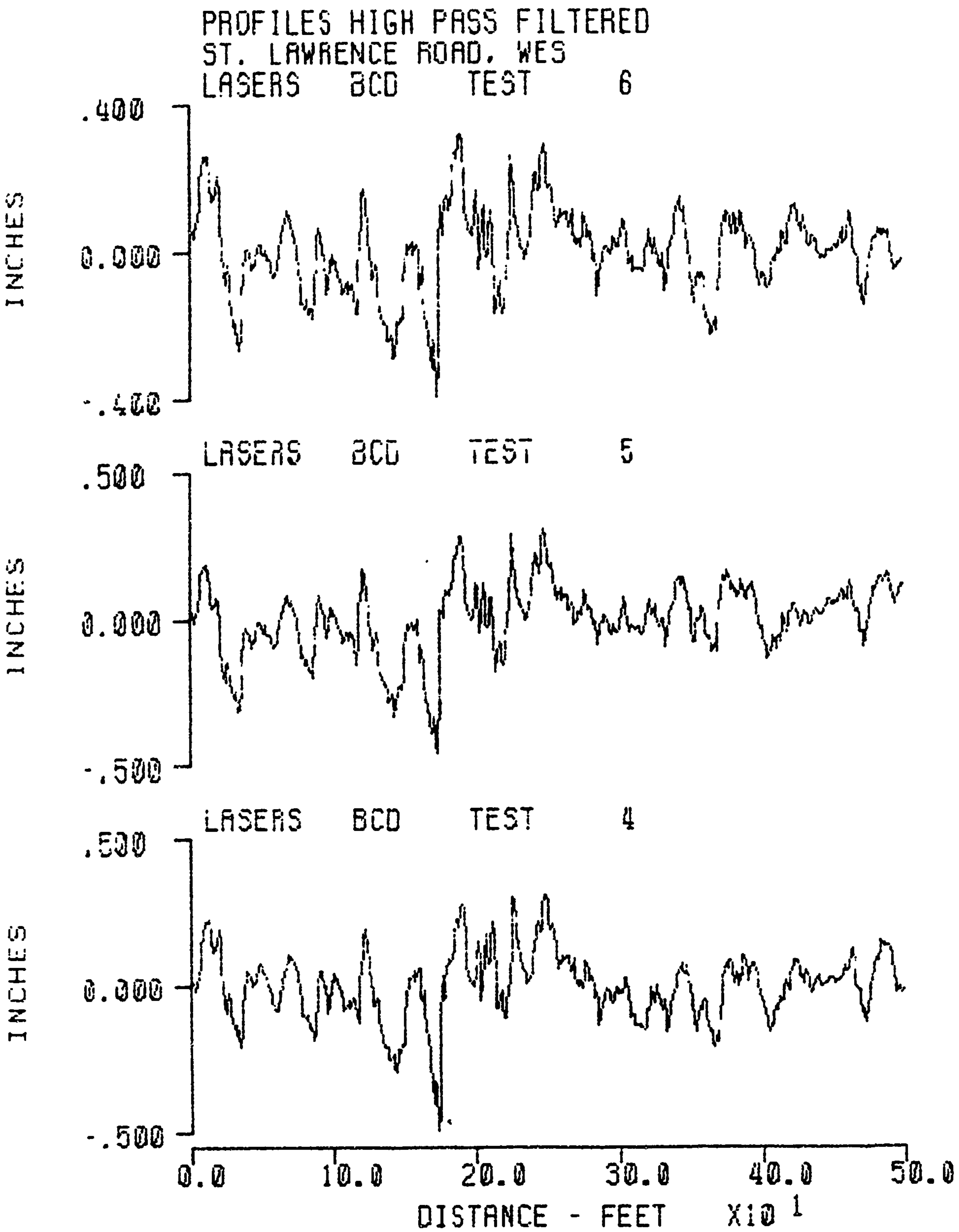

PROFILES WITH DELTA B AND DELTA C CORRECTIONS
ST. LAWRENCE ROAD, WES
LASERS BCD TEST 6
20.0
0.0
-20.0
INCHES
LASERS BCD TEST 5
20.0
0.0
-20.0
INCHES X10¹
LASERS BCD TEST 4
10.0
0.0
-10.0
INCHES
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE - FEET X10 1

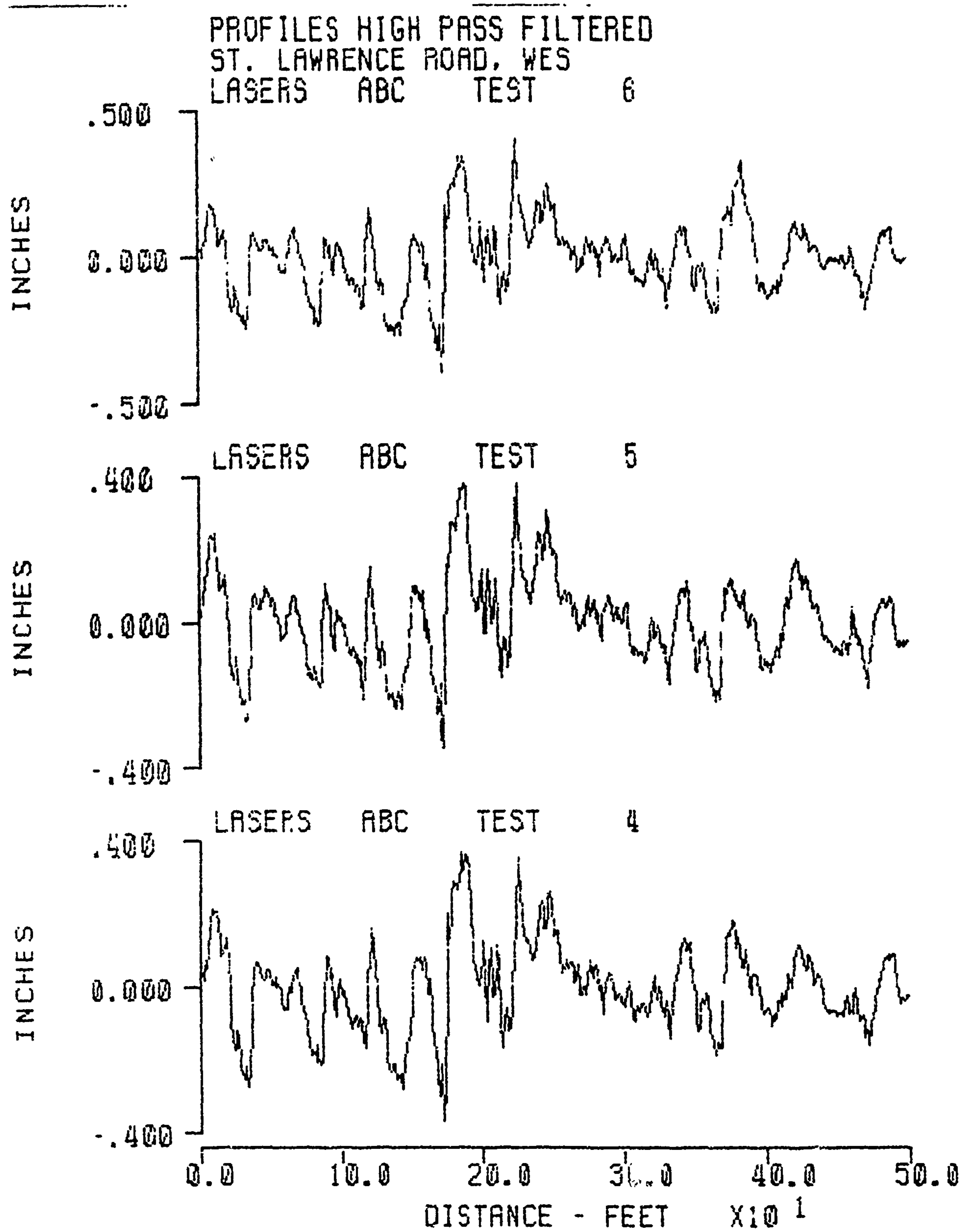

PROFILES WITH DELTA B AND DELTA C CORRECTIONS
ST. LAWRENCE ROAD, WES
LASERS ABC TEST 6
40.0
0.0
-40.0
INCHES
LASERS ABC TEST 5
40.0
0.0
-40.0
INCHES
LASERS ABC TEST 4
40.0
0.0
-40.0
INCHES
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE - FEET X10 1



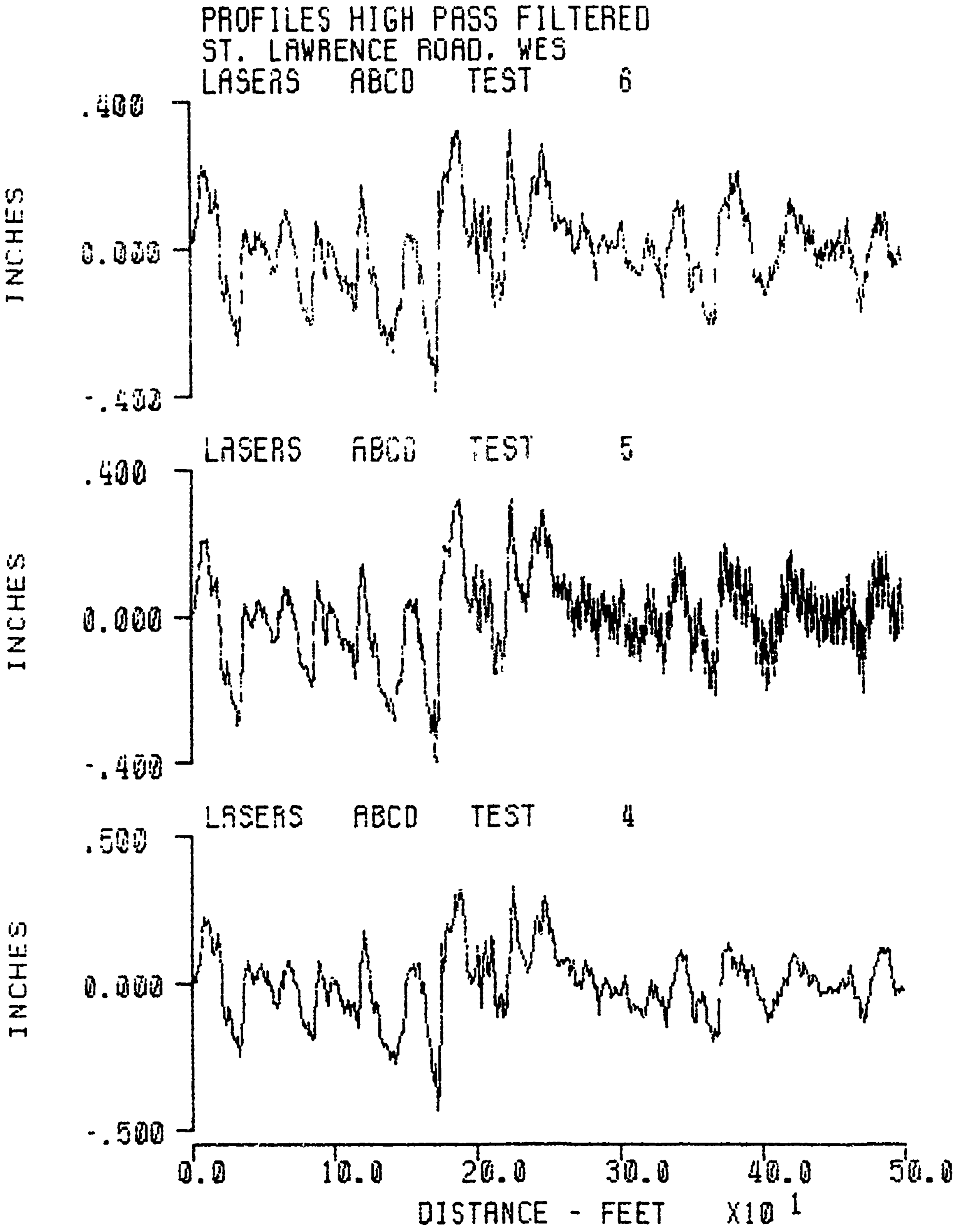
PROFILES WITH DELTA B AND DELTA C CORRECTIONS
ST. LAWRENCE ROAD, WES
LASERS ABCD TEST 6
40.0
0.0
-40.0
INCHES
LASERS ABCD TEST 5
50.0
0.0
-50.0
INCHES
LASERS ABCD TEST 4
20.0
0.0
-20.0
INCHES
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE - FEET X10 1

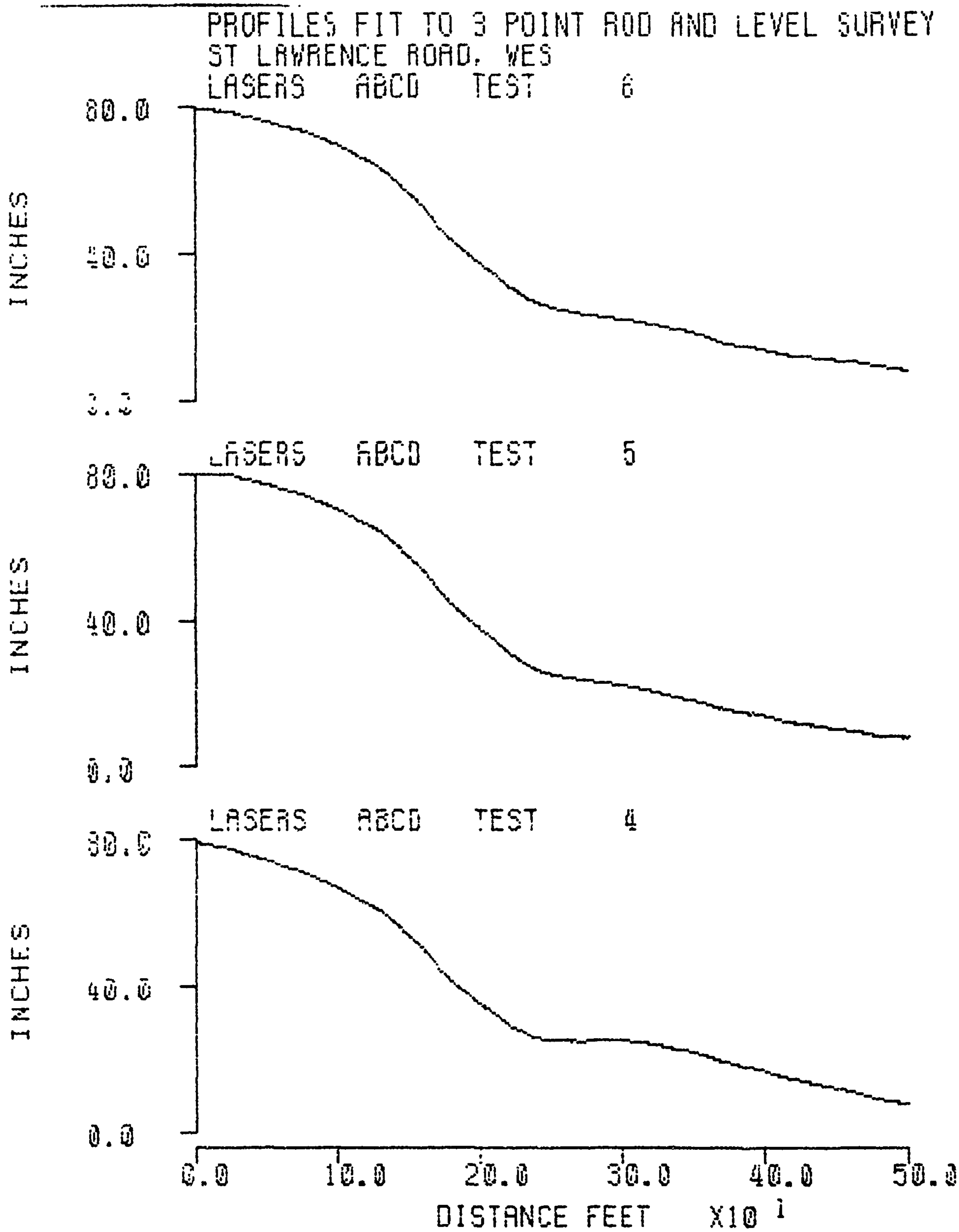

PROFILES HIGH PASS FILTERED
ST. LAWRENCE ROAD, WES
LASERS ABD TEST 6
.400
0.000
-.400
INCHES
LASERS ABD TEST 5
.400
0.000
-.400
INCHES
LASERS ABD TEST 4
.500
0.000
-.500
INCHES
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE - FEET X10 1

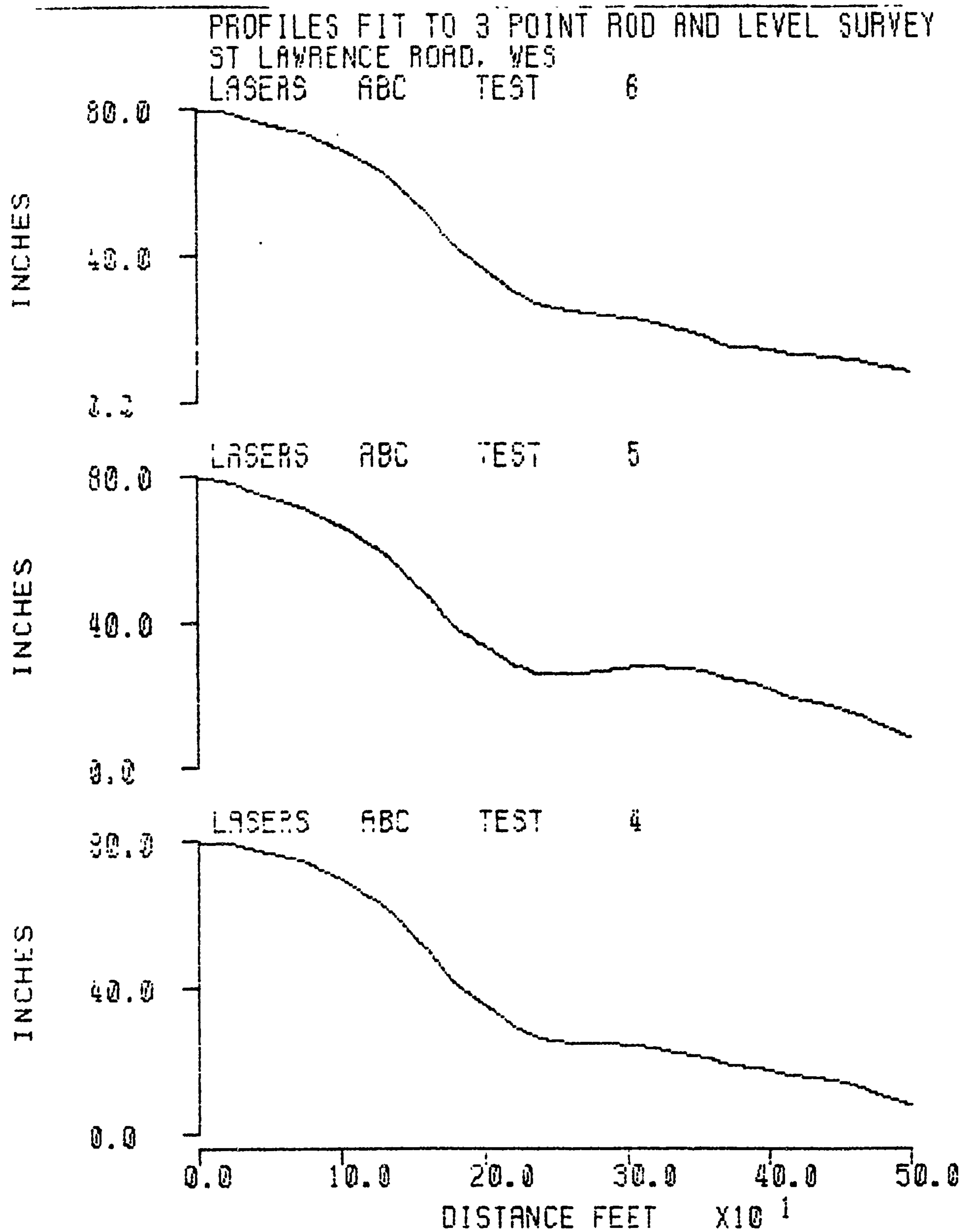

PROFILES HIGH PASS FILTERED
ST. LAWRENCE ROAD, WES
LASERS BCD TEST 6
.400
0.000
-.400
INCHES
LASERS BCD TEST 5
.500
0.000
-.500
INCHES
LASERS BCD TEST 4
.500
0.000
-.500
INCHES
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE - FEET X10 1

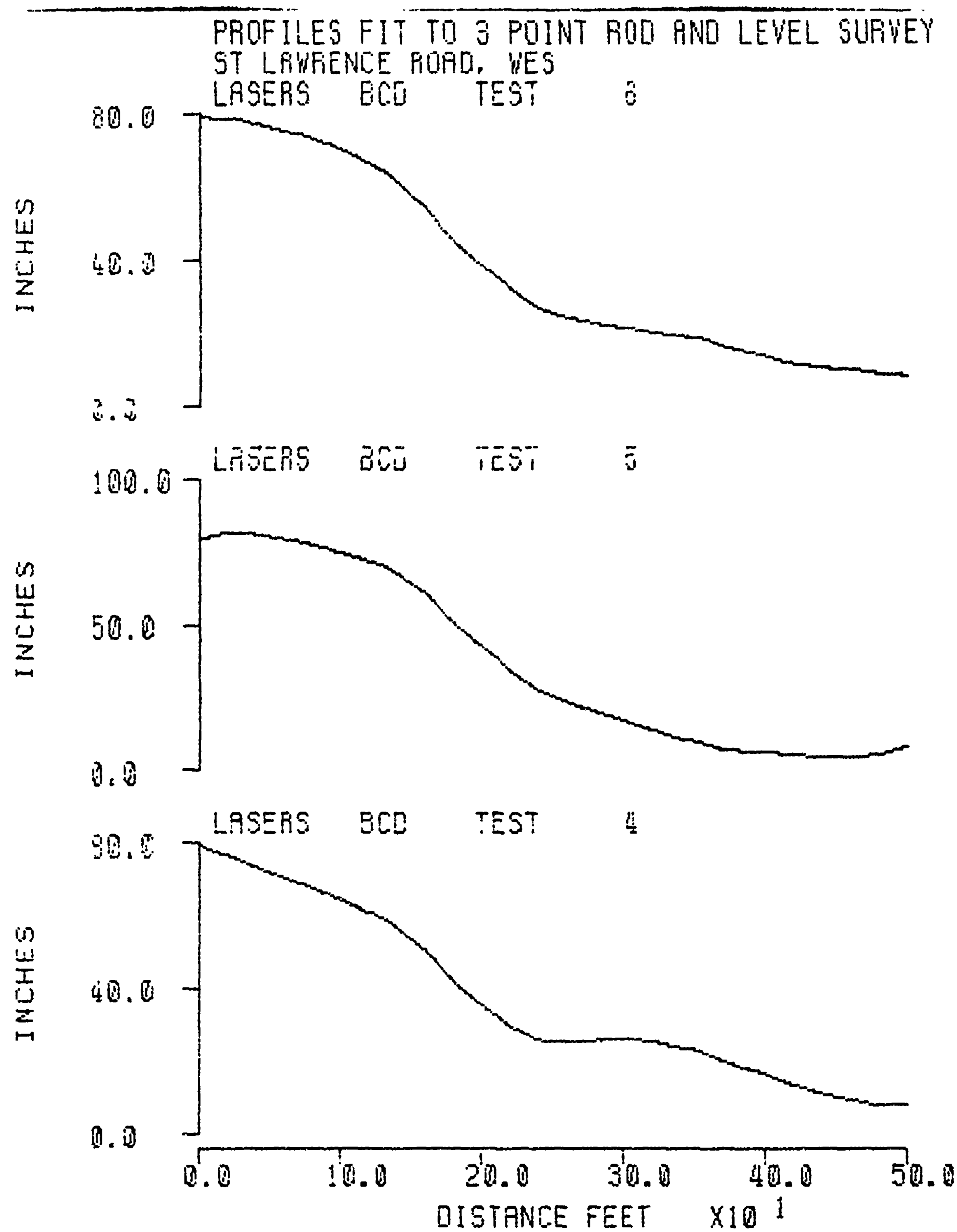


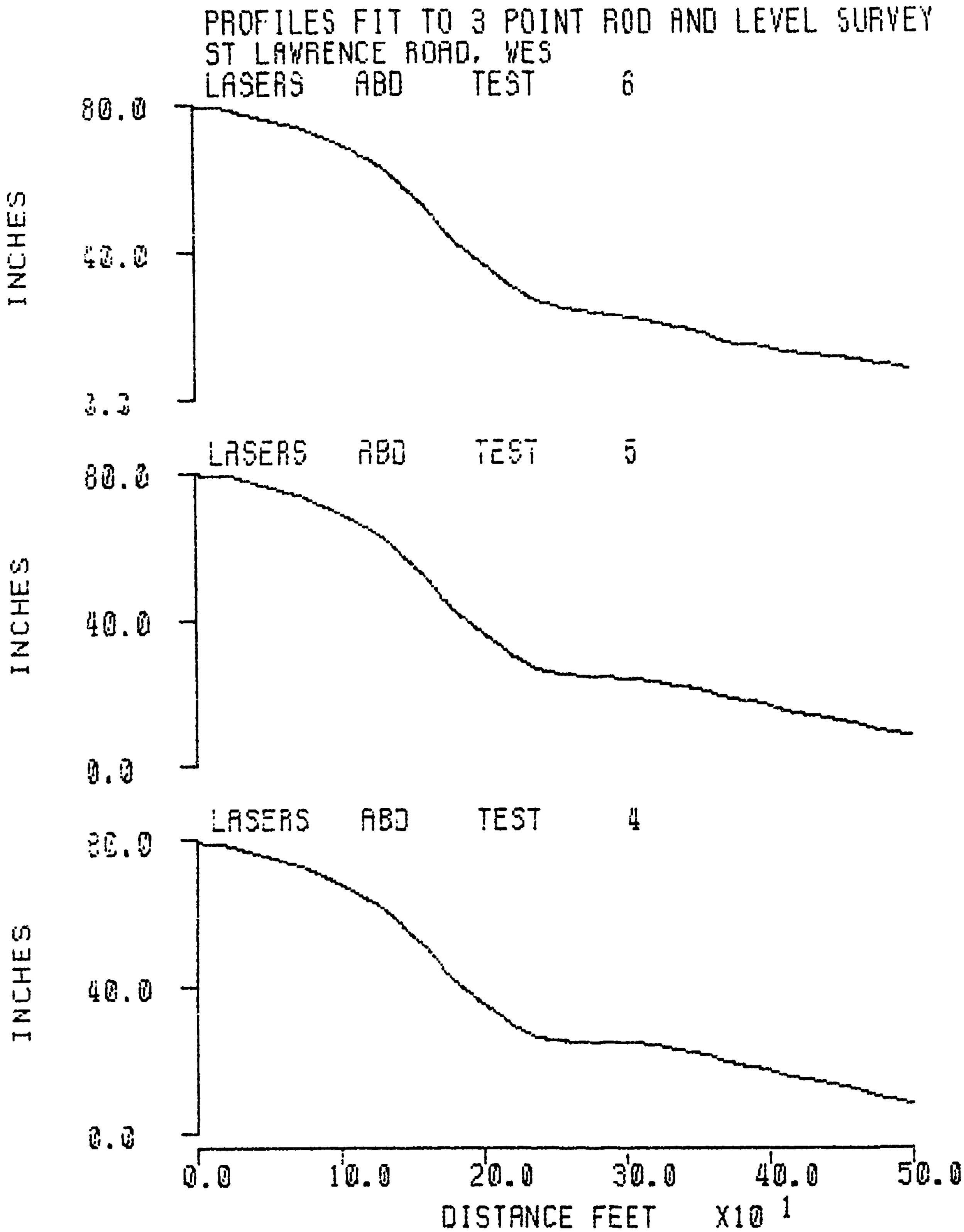
PROFILES HIGH PASS FILTERED
ST. LAWRENCE ROAD, WES
LASERS ABC TEST 6
.500
0.000
-.500
INCHES
LASERS ABC TEST 5
.400
0.000
-.400
INCHES
LASERS ABC TEST 4
.400
0.000
-.400
INCHES
0.0
10.0
20.0
40.0
50.0
DISTANCE - FEET X10 1


PROFILES HIGH PASS FILTERED
ST. LAWRENCE ROAD, WES
LASERS ABCD TEST 6
.400
0.000
-.400
INCHES
LASERS ABCD TEST 5
.400
0.000
-.400
INCHES
LASERS ABCD TEST 4
.500
0.000
-.500
INCHES
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE - FEET X10 1

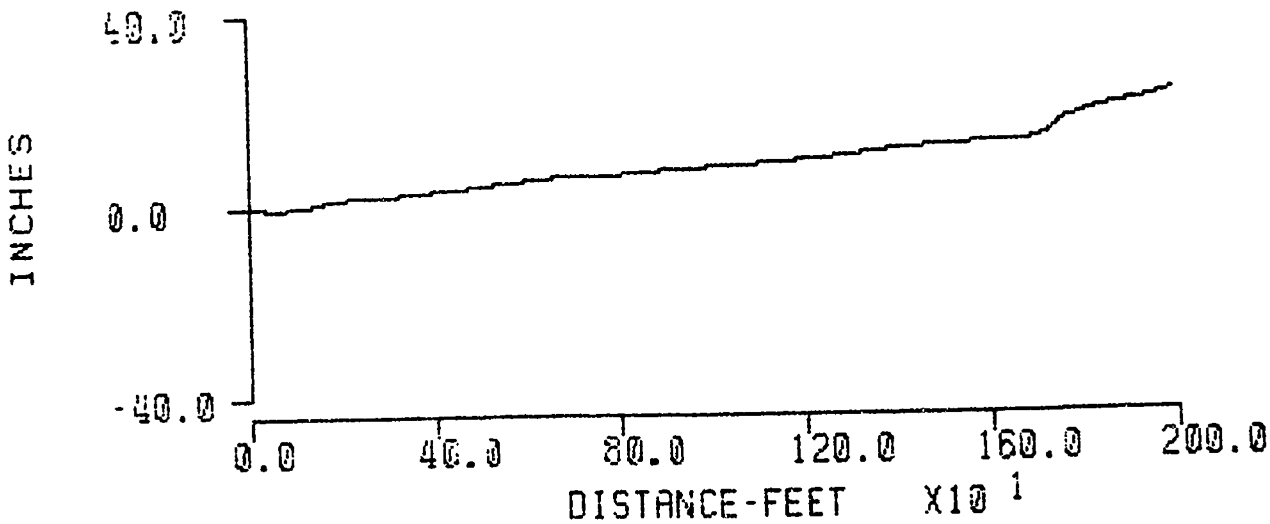

PROFILES FIT TO 3 POINT ROD AND LEVEL SURVEY
ST LAWRENCE ROAD, WES
LASERS ABCD TEST 6
80.0
40.0
INCHES
LASERS ABCD TEST 5
80.0
40.0
0.0
INCHES
LASERS ABCD TEST 4
40.0
0.0
INCHES
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE FEET X10 1

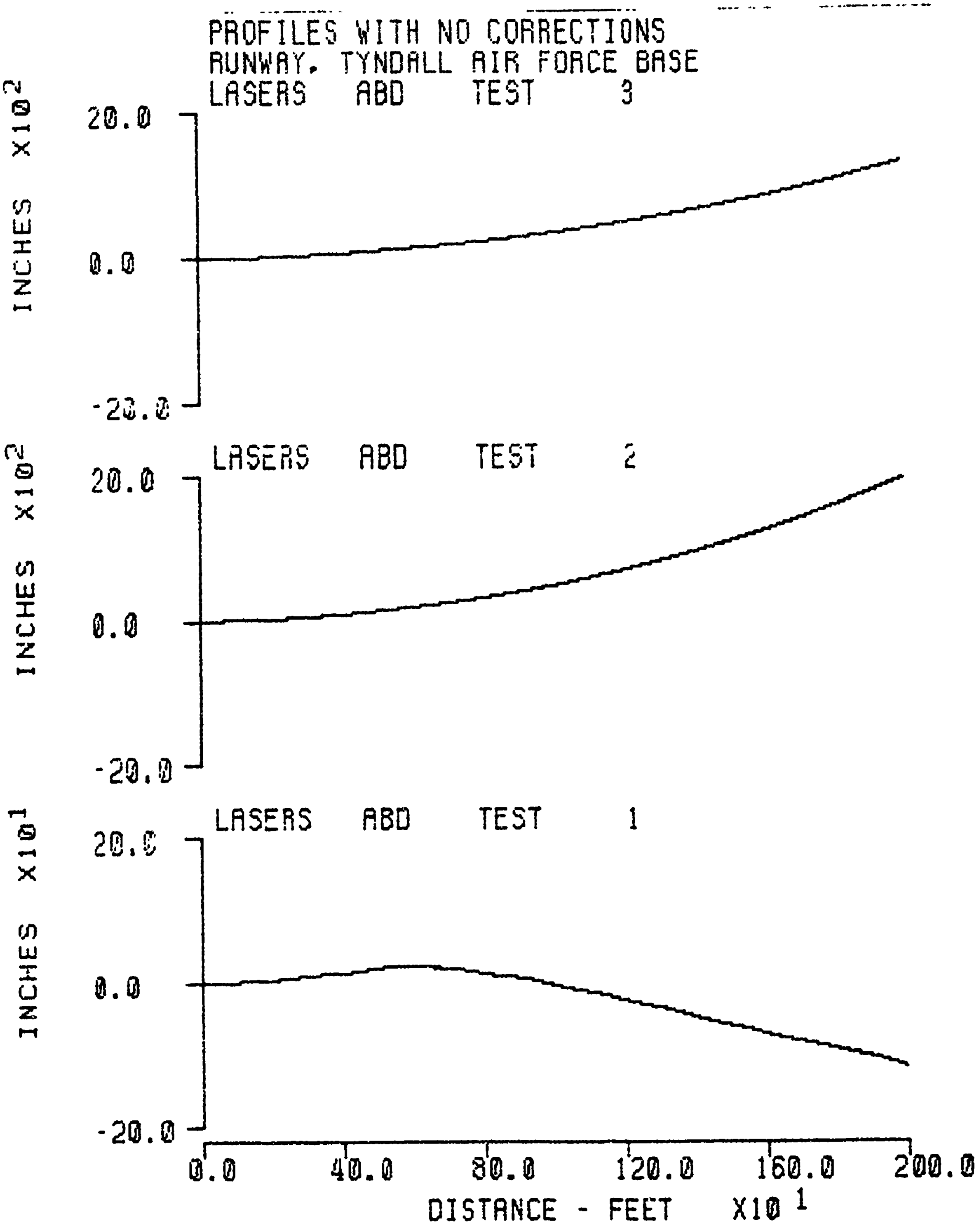

PROFILES FIT TO 3 POINT ROD AND LEVEL SURVEY
ST LAWRENCE ROAD, WES
LASERS ABC TEST 6
80.0
40.0
INCHES
LASERS ABC TEST 5
80.0
40.0
0.0
INCHES
LASERS ABC TEST 4
40.0
0.0
INCHES
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE FEET X10 1

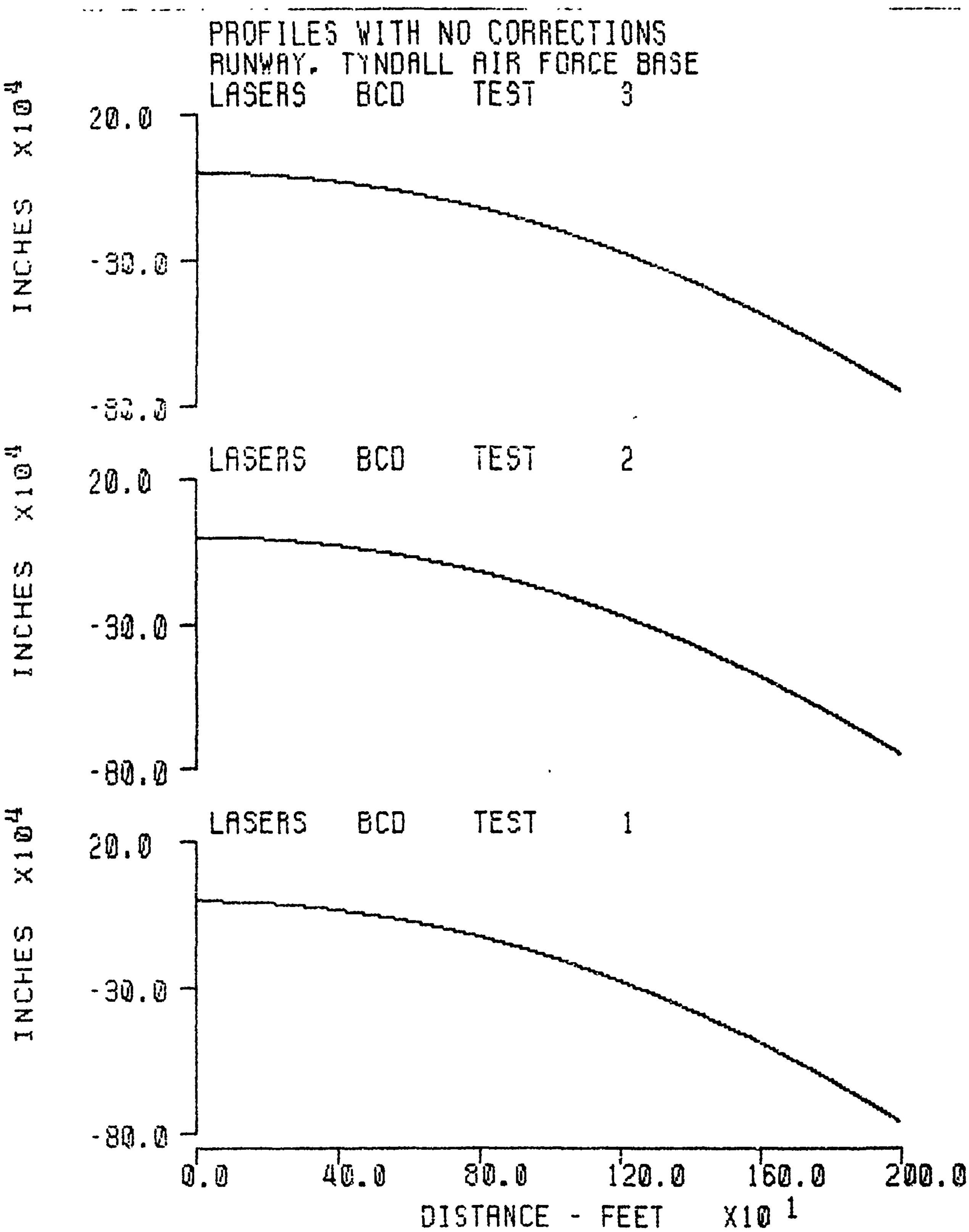

PROFILES FIT TO 3 POINT ROD AND LEVEL SURVEY
ST LAWRENCE ROAD, WES
LASERS BCD TEST 6
80.0
40.0
INCHES
LASERS BCD TEST 5
100.0
50.0
0.0
INCHES
LASERS BCD TEST 4
80.0
40.0
0.0
INCHES
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE FEET X10 1

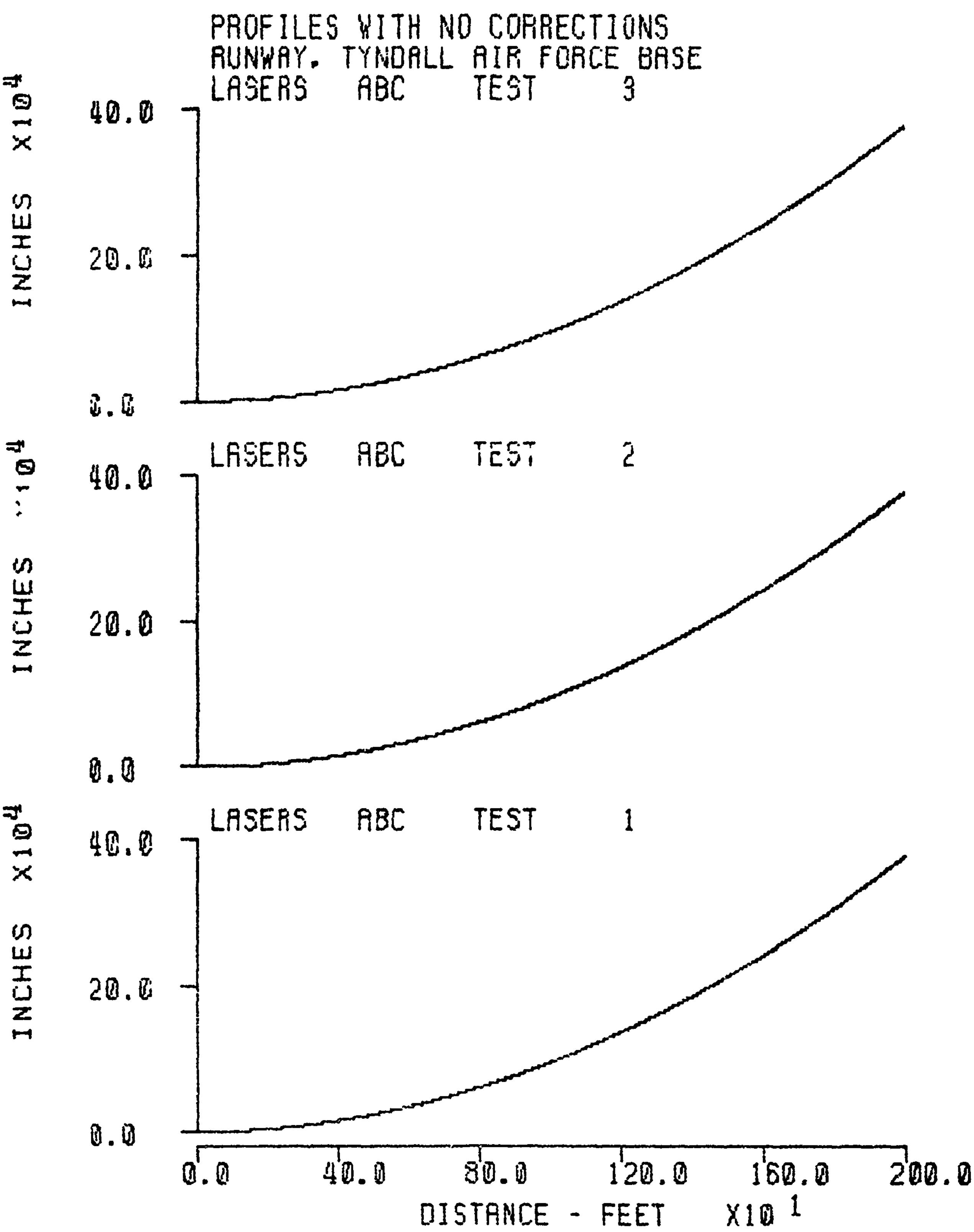

PROFILES FIT TO 3 POINT ROD AND LEVEL SURVEY
ST LAWRENCE ROAD, WES
LASERS ABD TEST 6
80.0
40.0
0.0
INCHES
LASERS ABD TEST 5
80.0
40.0
0.0
INCHES
LASERS ABD TEST 4
80.0
40.0
0.0
INCHES
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE FEET X10 1

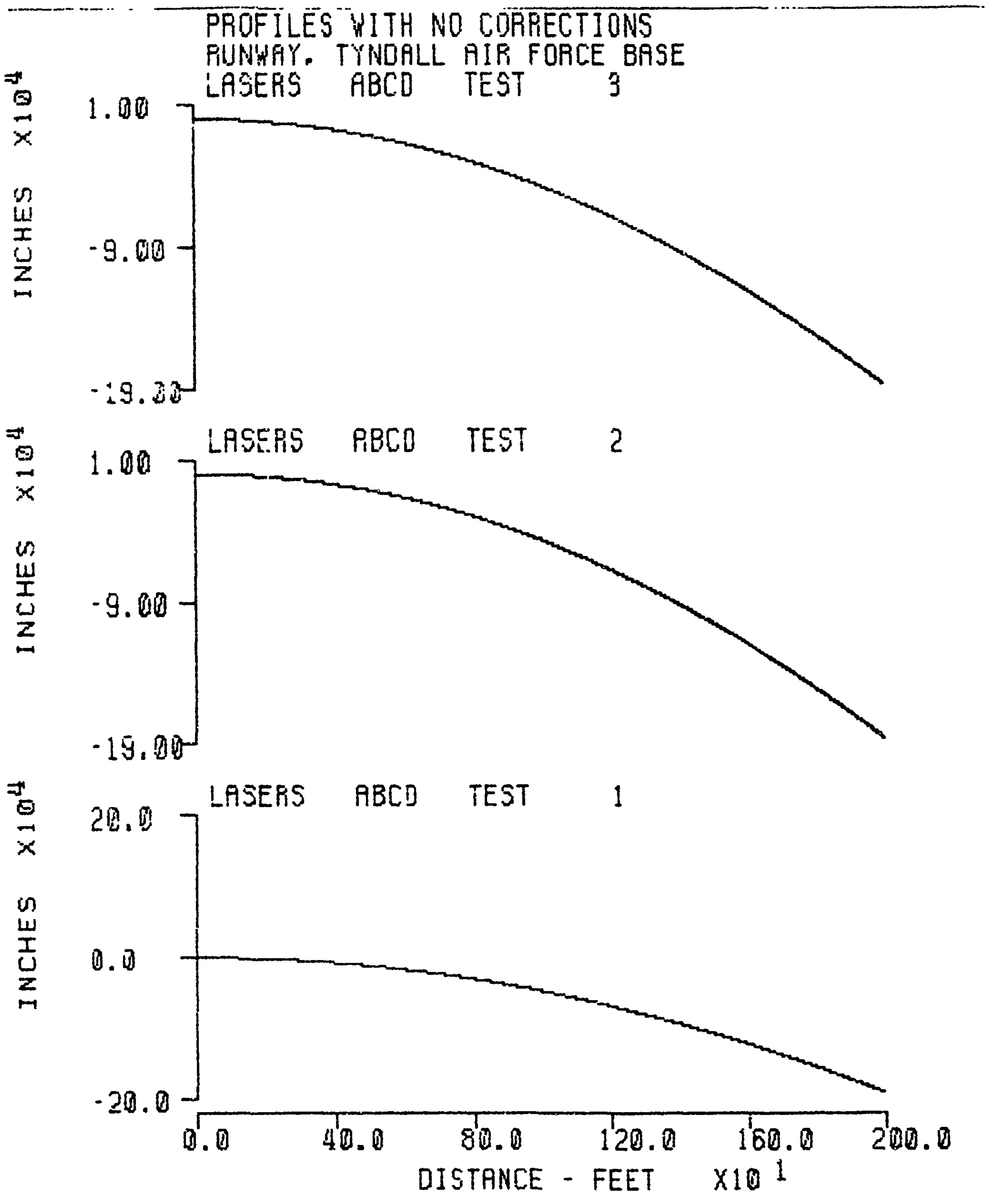
RUNWAY AT TYNDALL AIR FORCE BASE
PROFILE FROM ROD AND LEVEL SURVEY

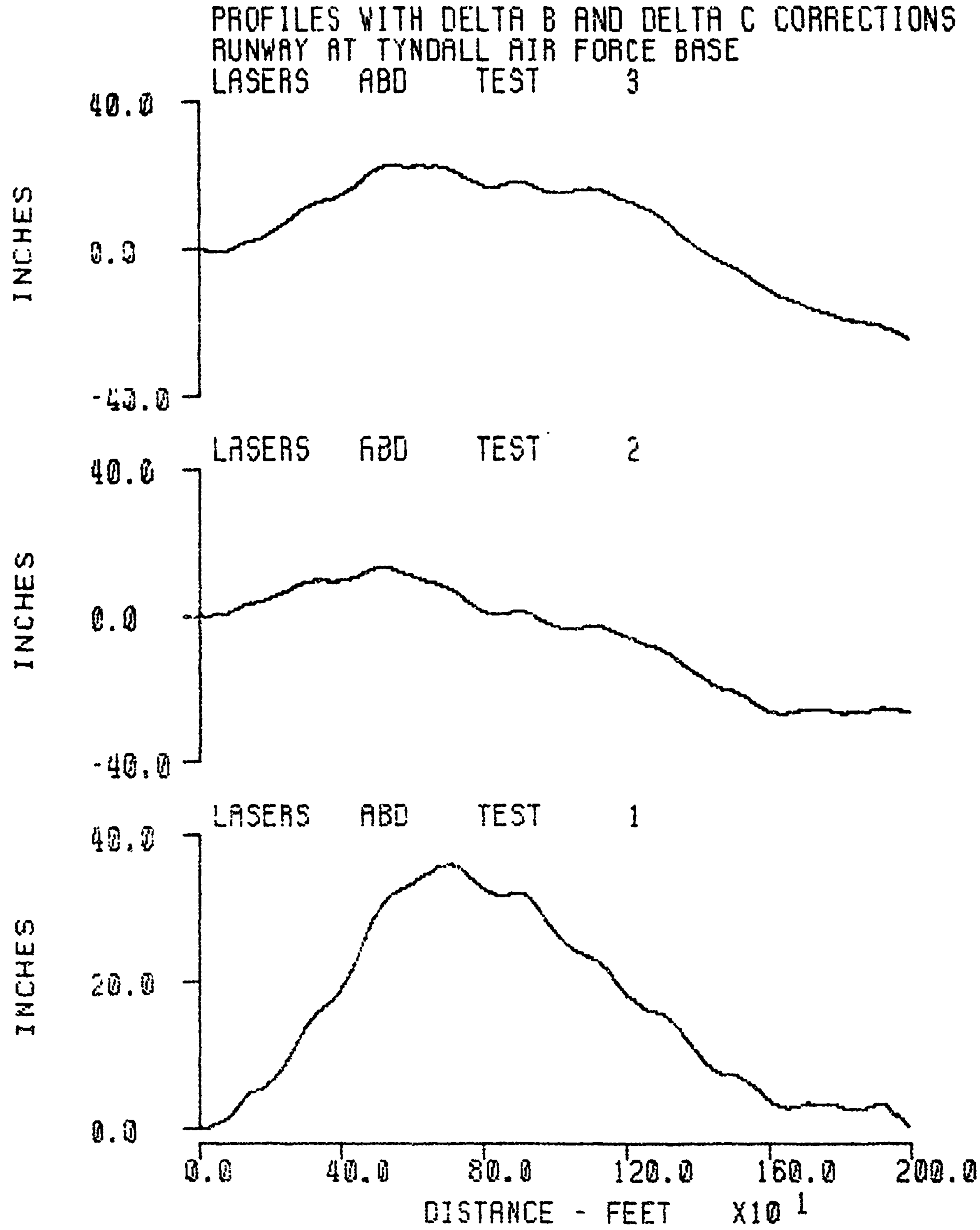


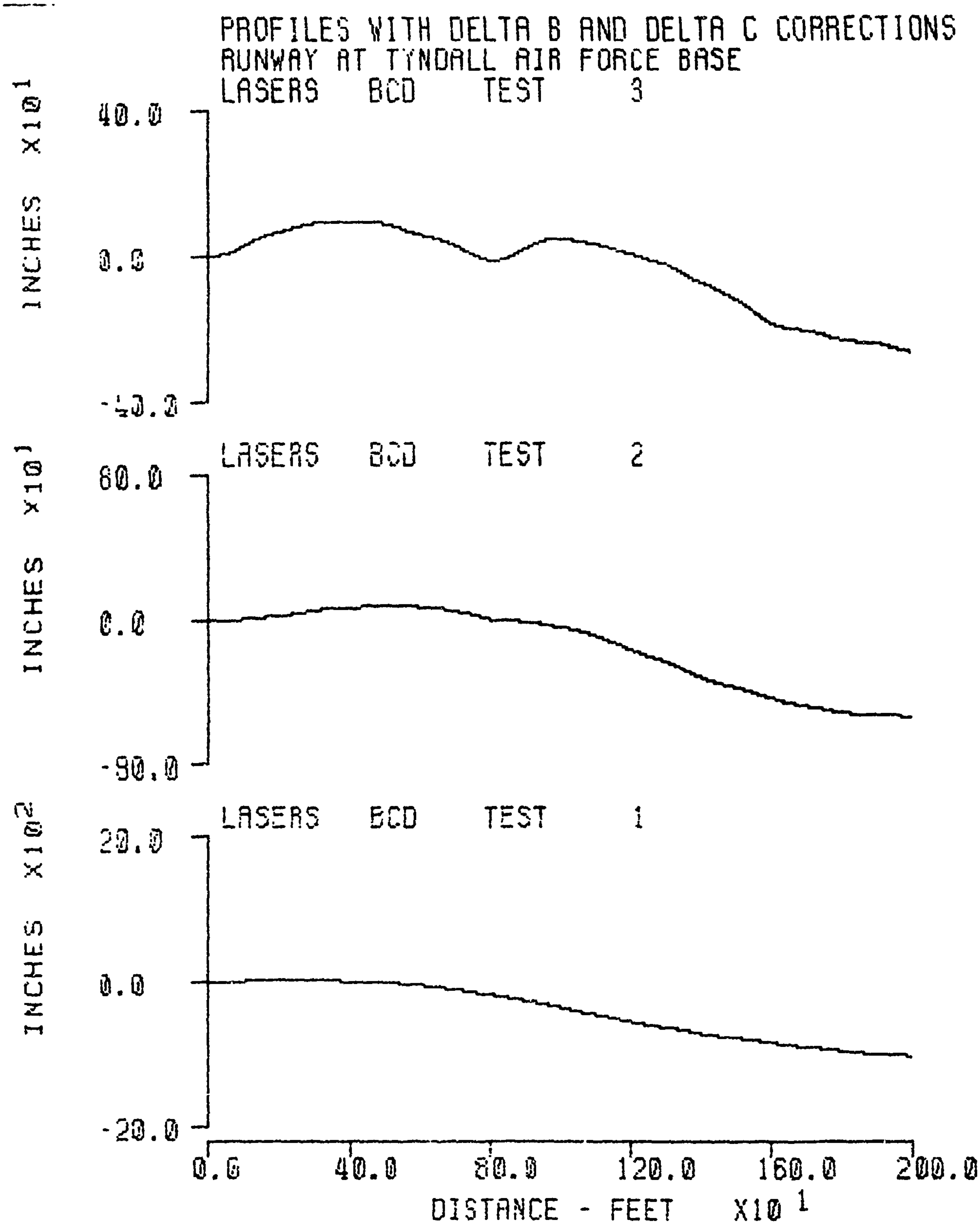

PROFILES WITH NO CORRECTIONS
RUNWAY, TYNDALL AIR FORCE BASE
LASERS ABD TEST 3
INCHES X10^2
20.0
0.0
-20.0
LASERS ABD TEST 2
INCHES X10^2
20.0
0.0
-20.0
LASERS ABD TEST 1
INCHES X10^1
20.0
0.0
-20.0
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE - FEET X10 1

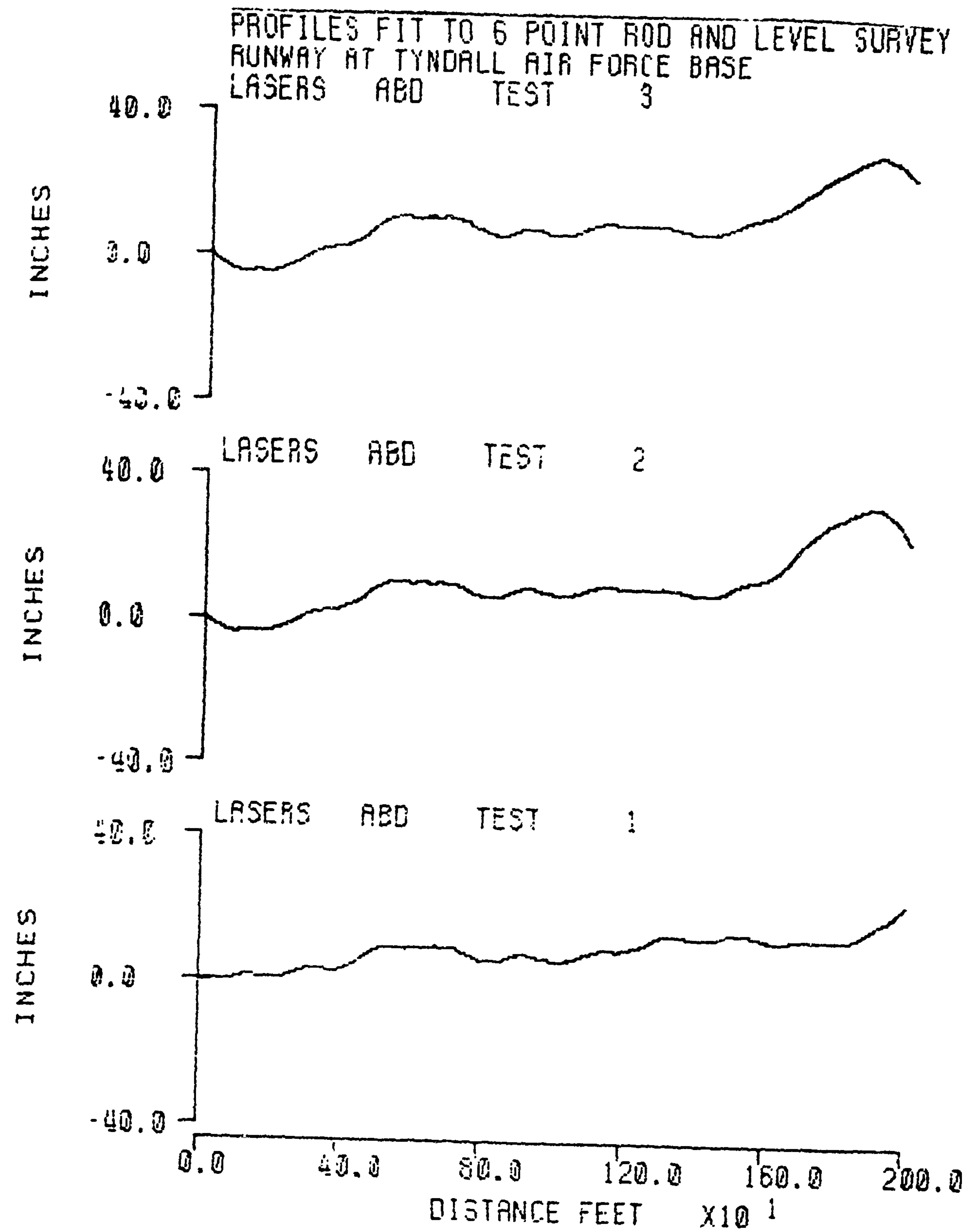

PROFILES WITH NO CORRECTIONS
RUNWAY, TYNDALL AIR FORCE BASE
LASERS BCD TEST 3
LASERS BCD TEST 2
LASERS BCD TEST 1
INCHES X10^4
20.0
-30.0
-80.0
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE - FEET X10 1

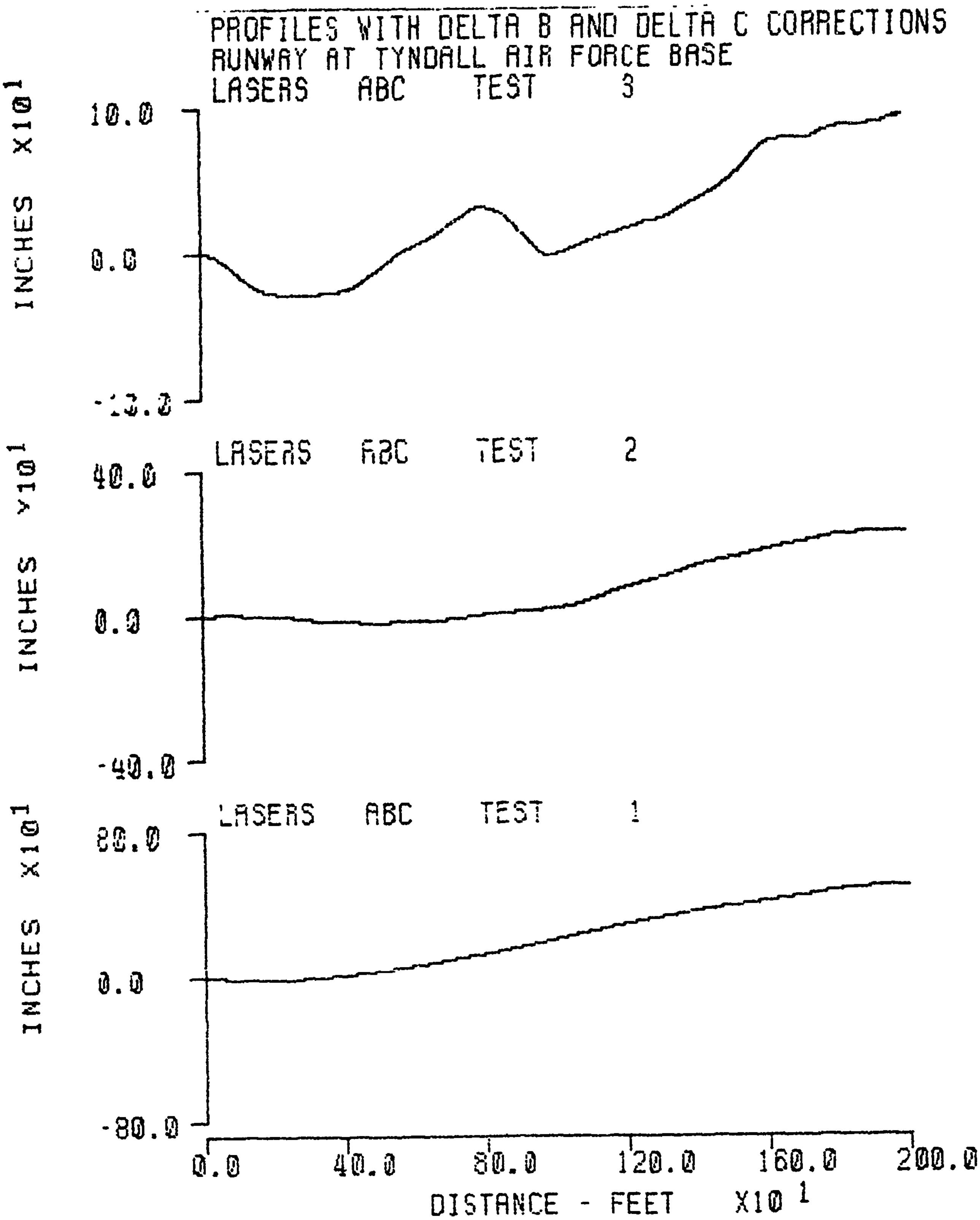

PROFILES WITH NO CORRECTIONS
RUNWAY, TYNDALL AIR FORCE BASE
LASERS ABC TEST 3
LASERS ABC TEST 2
LASERS ABC TEST 1
INCHES X10^4
40.0
20.0
0.0
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE - FEET X10 1


PROFILES WITH NO CORRECTIONS
RUNWAY, TYNDALL AIR FORCE BASE
LASERS ABCD TEST 3
INCHES X10^4
1.00
-9.00
-19.00
LASERS ABCD TEST 2
INCHES X10^4
1.00
-9.00
-19.00
LASERS ABCD TEST 1
INCHES X10^4
20.0
0.0
-20.0
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE - FEET X10 1


PROFILES WITH DELTA B AND DELTA C CORRECTIONS
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABD TEST 3
40.0
0.0
-40.0
INCHES
LASERS ABD TEST 2
40.0
0.0
-40.0
INCHES
LASERS ABD TEST 1
40.0
20.0
0.0
INCHES
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE - FEET X10 1


PROFILES WITH DELTA B AND DELTA C CORRECTIONS
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS BCD TEST 3
INCHES X10 1
40.0
0.0
-40.0
LASERS BCD TEST 2
INCHES X10 1
80.0
0.0
-80.0
LASERS BCD TEST 1
INCHES X10 2
20.0
0.0
-20.0
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE - FEET X10 1


PROFILES FIT TO 6 POINT ROD AND LEVEL SURVEY
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABD TEST 3
40.0
INCHES
-40.0
LASERS ABD TEST 2
40.0
INCHES
0.0
-40.0
LASERS ABD TEST 1
INCHES
0.0
-40.0
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE FEET X10 1


PROFILES WITH DELTA B AND DELTA C CORRECTIONS
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABC TEST 3
INCHES X10^1
10.0
0.0
LASERS ABC TEST 2
40.0
0.0
-40.0
LASERS ABC TEST 1
0.0
-80.0
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE - FEET X10 1

APPENDIX B

DERIVATION OF PROFILE ALGORITHM

A rigid beam has 3 lasers mounted on it to measure the distance from the beam to the pavement. This can be seen in Figure B-1. Symbols in the figure are defined as follows:

a = distance from beam to pavement at laser 1

b = distance from beam to pavement at laser 2

c = distance from beam to pavement at laser 3

A = distance from bean to datum at laser 1

B = distance from beam to datum at laser 2

C = distance from beam to datum at laser 3

y = distance from laser 1 to laser 2

z = distance from laser 2 to laser 3

(z must be an integer multiply of y)

From Figure B-1, it is seen that:

$$B + b = e + A + a$$

$$B + b = - f + C + c$$

$$e/f = y/z$$

Solving for A in terms of B , C , a , b, c :

$$A=B \times (y/z + 1) - (y/z) \times C - a + b \times (y/z + 1) - (y/z) \times c$$

After A has been calculated, the beam can be moved forward and the previous value of B can now be used for C . The previous value of A can be used for B . This can continue to the end of the profile.

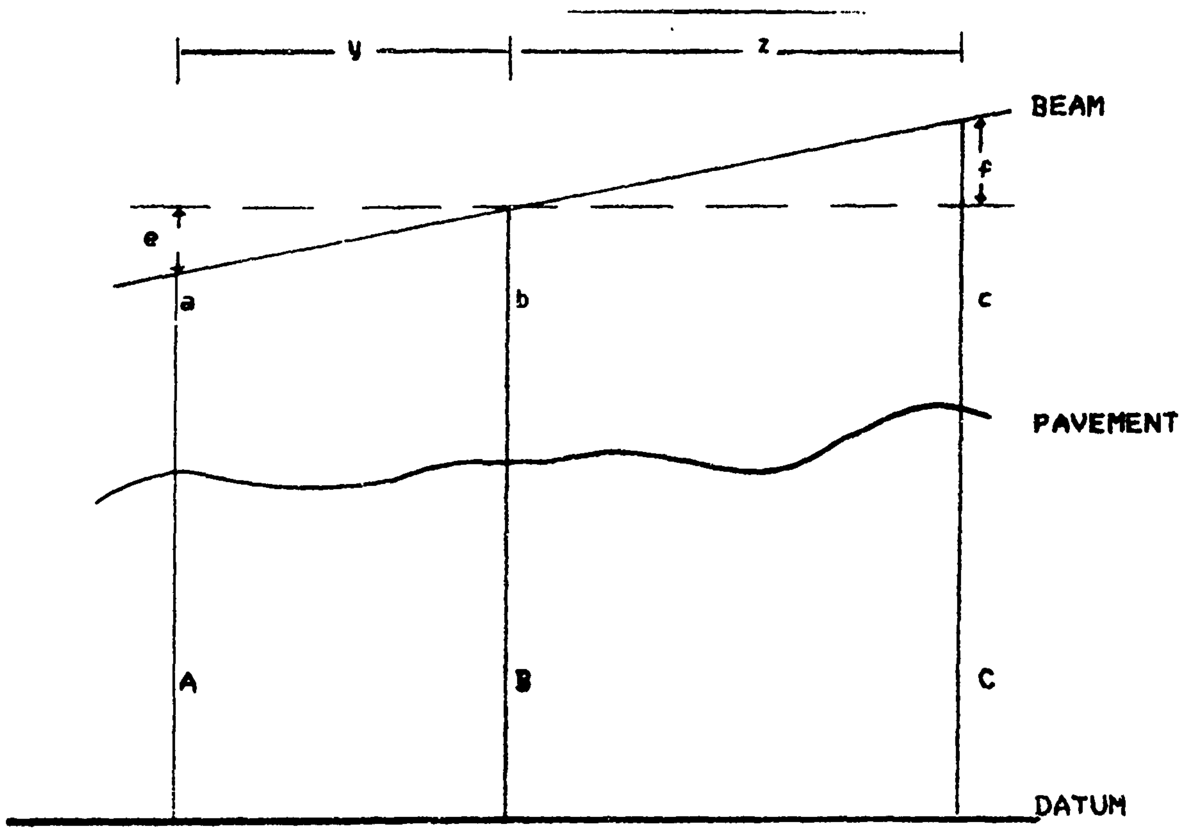


Figure B-1. Rigid beam with three lasers

APPENDIX C

TOTAL ERROR FORMULA

The algorithm used for a symmetric laser configuration is:

$$A = 2 \times B - C - a + 2 \times b - c$$

The first derivative of the profile can be expressed as:

$$A - B = B - C - a + 2 \times b - c$$

The second derivative of the profile can be expressed as:

$$(A - B) - (B + C) = -a + 2b - c$$

If there is a constant error, e , in the lasers, the profile can be expressed as:

$$\text{Profile} = \Sigma\ \Sigma\ (-a + 2b - c + e)$$

The error component is:

$$\text{Total error} = \Sigma\ \Sigma\ e$$

or

$$\text{Total error} = \iint e\ dX$$

$$\text{Total error} = e \times X\ dX + \int C1 dX$$

$$\text{Total error} = (e/2)X^2 + C1 \times X + C2$$

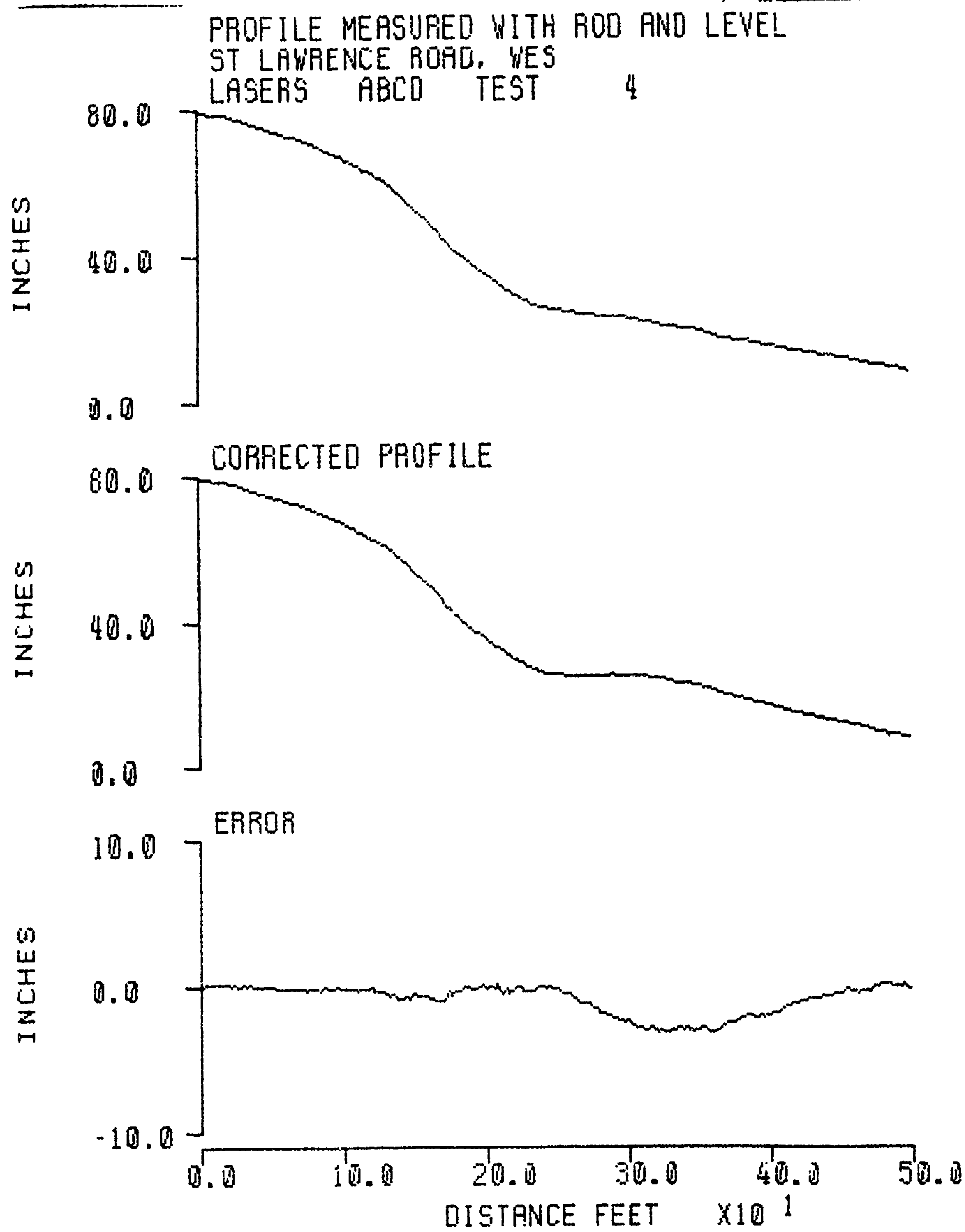
When X = 0 there is no error; therefore, C2 = 0

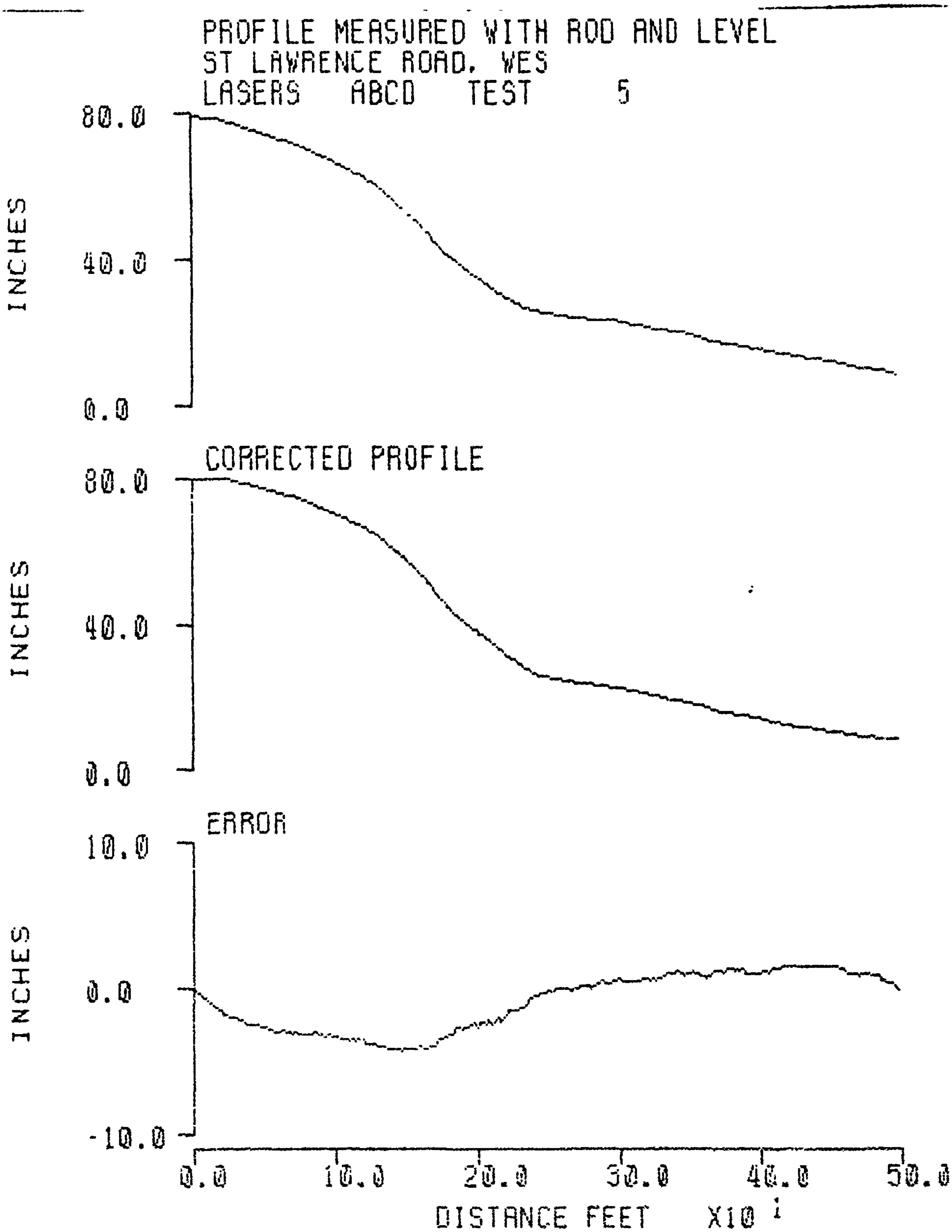
When X = 1, the error = e; therefore, C1 = (e/2)

$$\text{Total error} = (e/2) \times (X^2 + X)$$

APPENDIX D

ERROR PLOTS


PROFILE MEASURED WITH ROD AND LEVEL
ST LAWRENCE ROAD, WES
LASERS ABCD TEST 4
80.0
40.0
0.0
INCHES
CORRECTED PROFILE
80.0
40.0
0.0
INCHES
ERROR
10.0
0.0
-10.0
INCHES
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE FEET X10 1



PROFILE MEASURED WITH ROD AND LEVEL
ST LAWRENCE ROAD, WES
LASERS ABCD TEST 5
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40.0
0.0
INCHES
CORRECTED PROFILE
80.0
40.0
0.0
INCHES
ERROR
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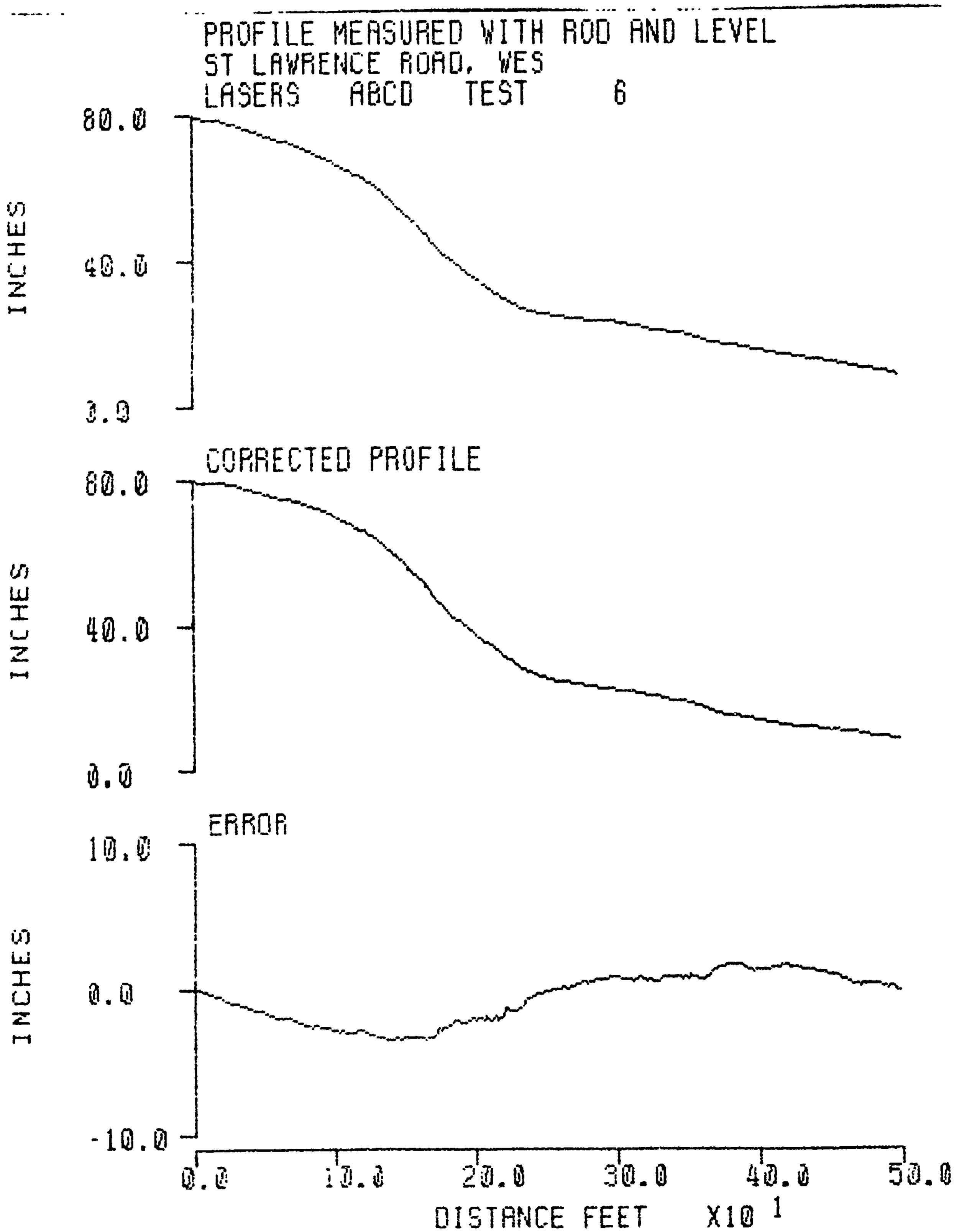
INCHES
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE FEET X10 1


PROFILE MEASURED WITH ROD AND LEVEL
ST LAWRENCE ROAD, WES
LASERS ABCD TEST 6
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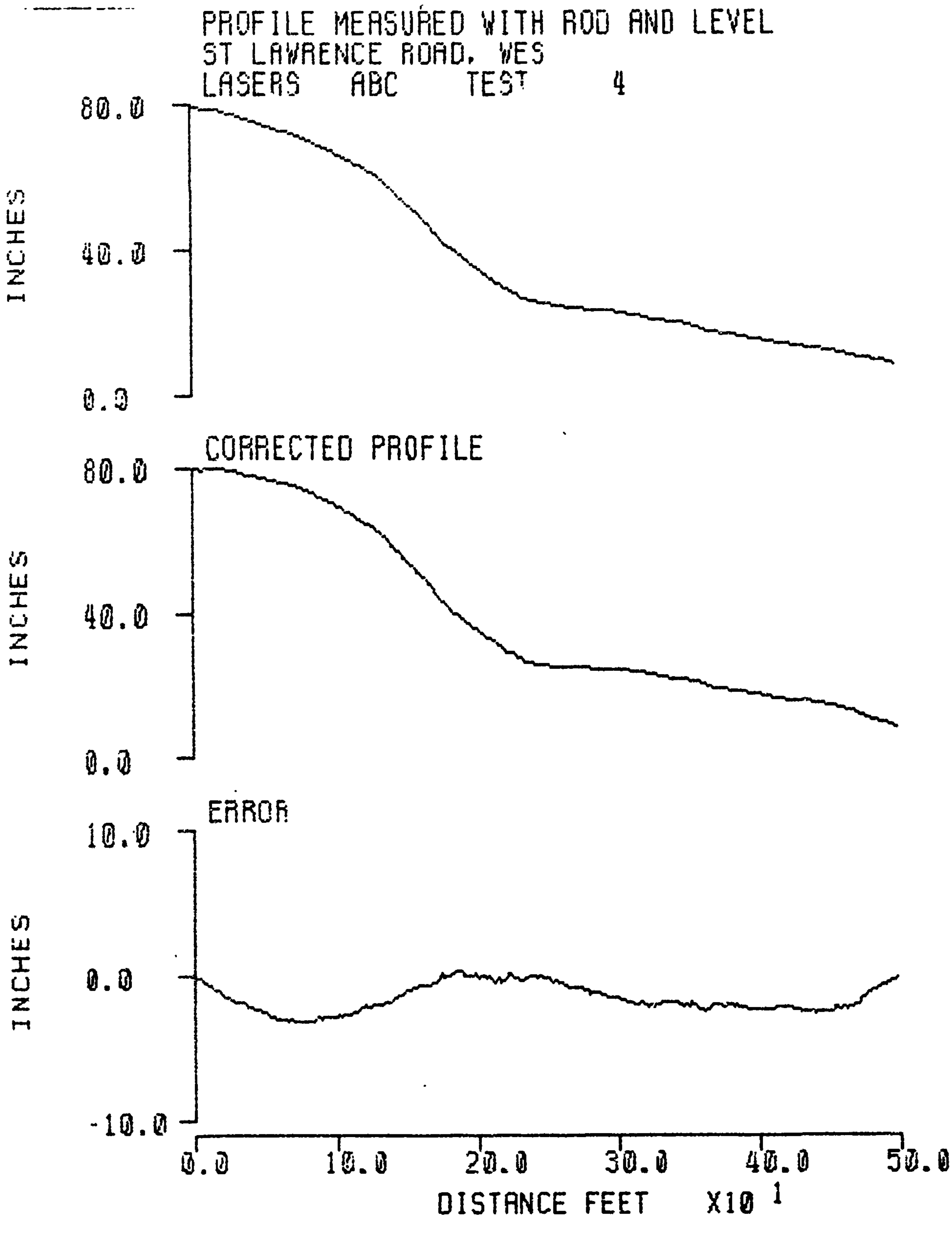
40.0
0.0
INCHES
CORRECTED PROFILE
80.0
40.0
0.0
INCHES
ERROR
10.0
0.0
-10.0
INCHES
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE FEET X10 1



PROFILE MEASURED WITH ROD AND LEVEL
ST LAWRENCE ROAD, WES
LASERS ABC TEST 4
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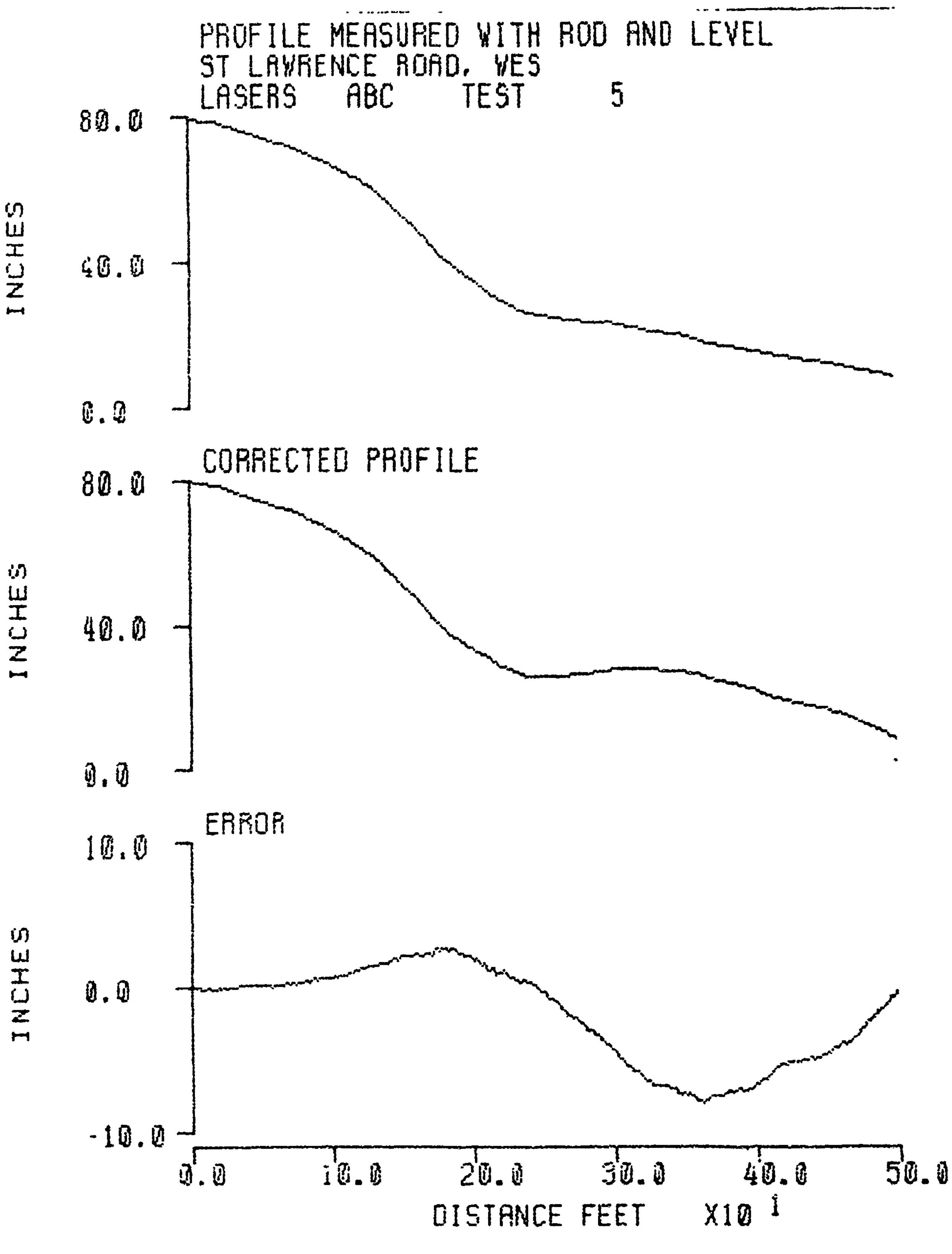
40.0
0.0
INCHES
CORRECTED PROFILE
80.0
40.0
0.0
INCHES
ERROR
10.0
0.0
-10.0
INCHES
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE FEET X10 1


PROFILE MEASURED WITH ROD AND LEVEL
ST LAWRENCE ROAD, WES
LASERS ABC TEST 5
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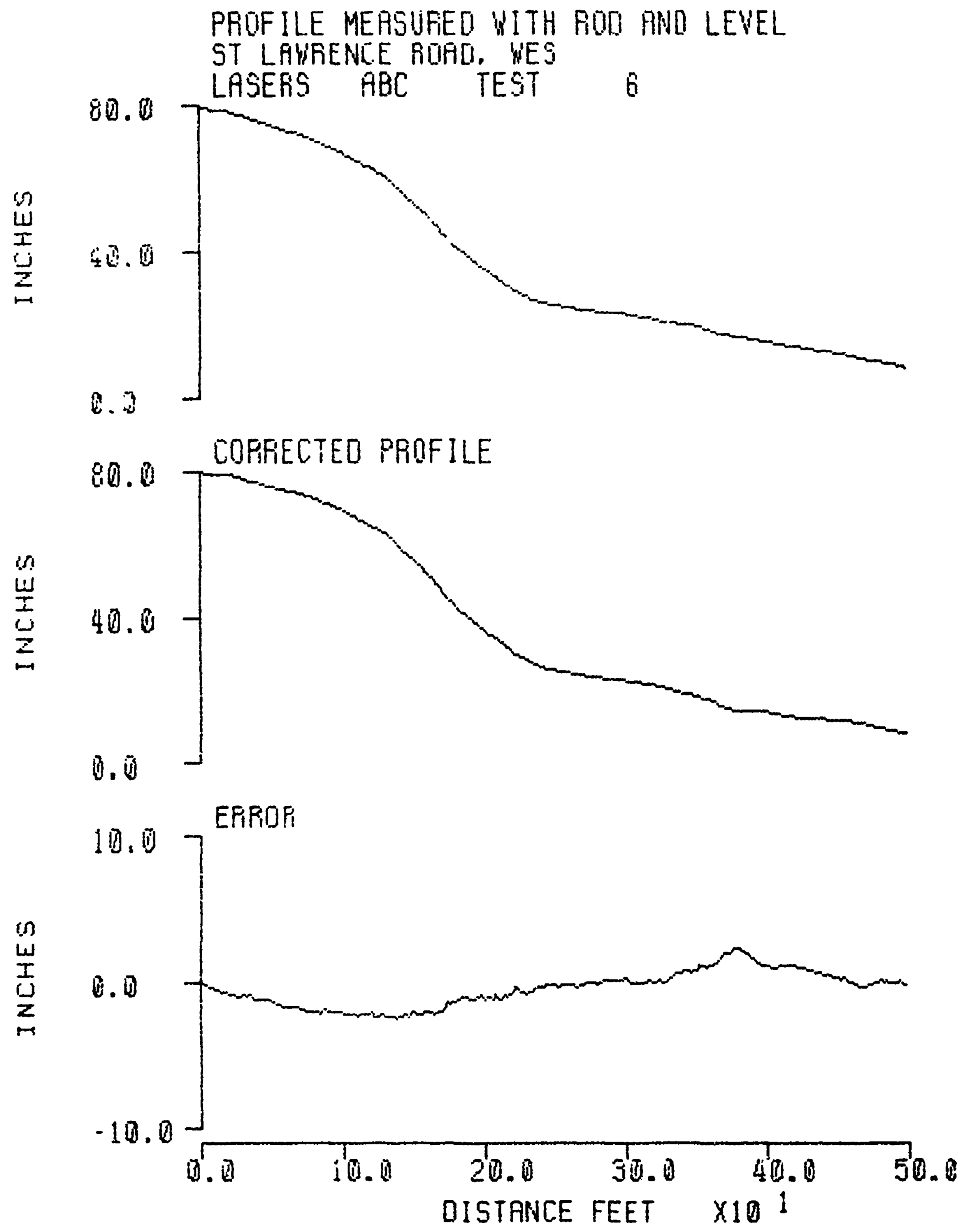
40.0
0.0
INCHES
CORRECTED PROFILE
80.0
40.0
0.0
INCHES
ERROR
10.0
0.0
-10.0
INCHES
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE FEET X10 1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ST LAWRENCE ROAD, WES
LASERS ABC TEST 6
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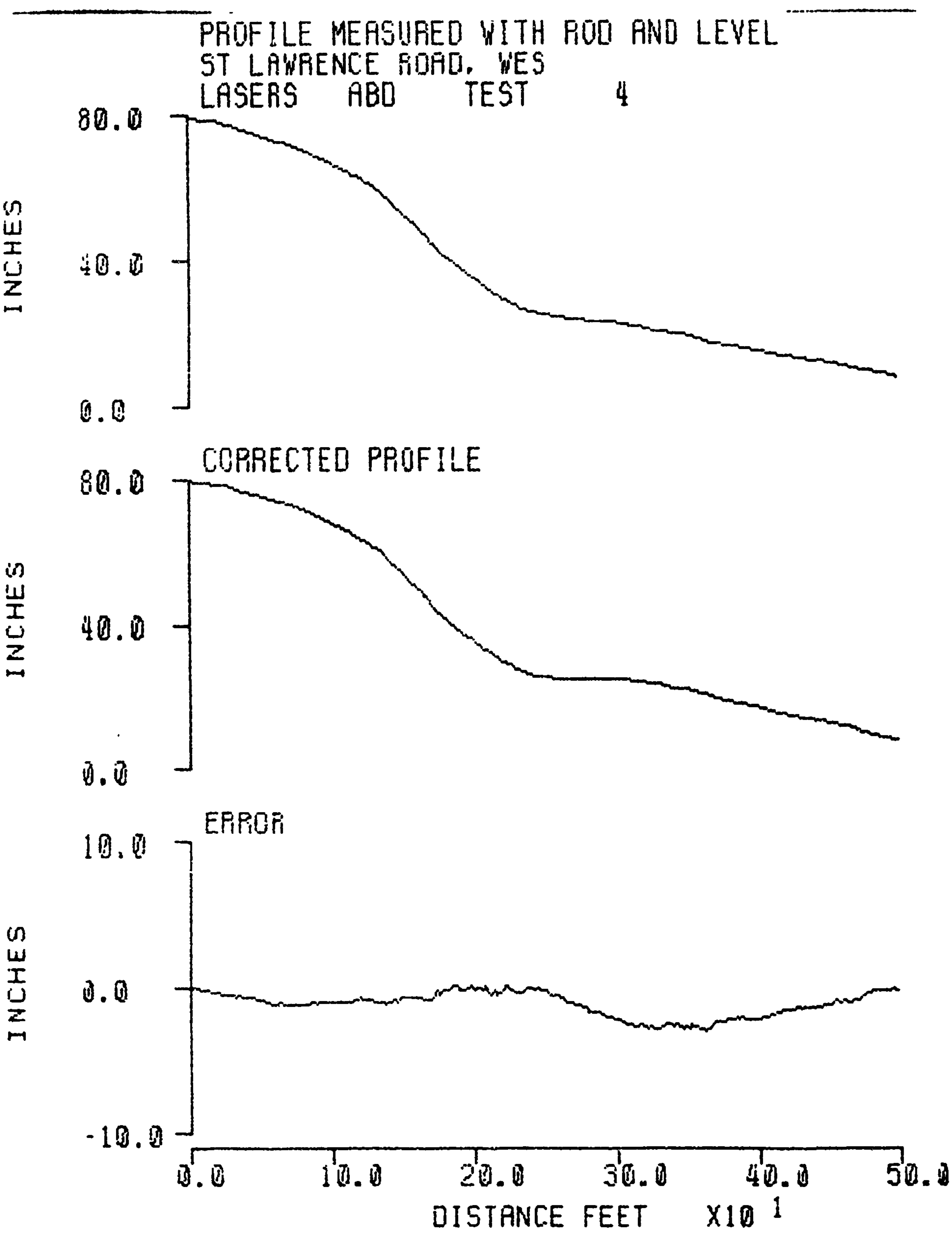
40.0
0.0
INCHES
CORRECTED PROFILE
80.0
40.0
0.0
INCHES
ERROR
10.0
0.0
-10.0
INCHES
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE FEET X10 1


PROFILE MEASURED WITH ROD AND LEVEL
ST LAWRENCE ROAD, WES
LASERS ABD TEST 4
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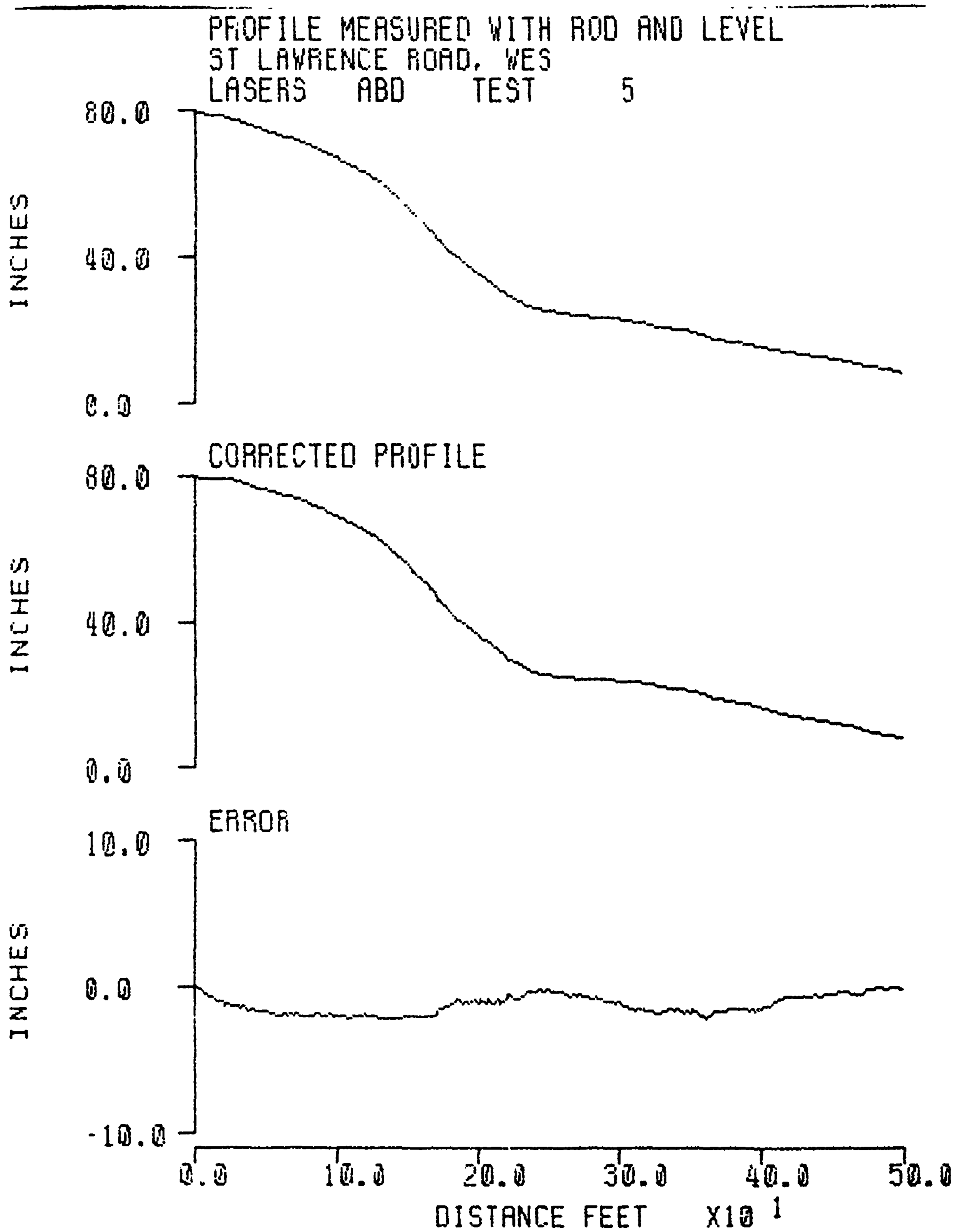
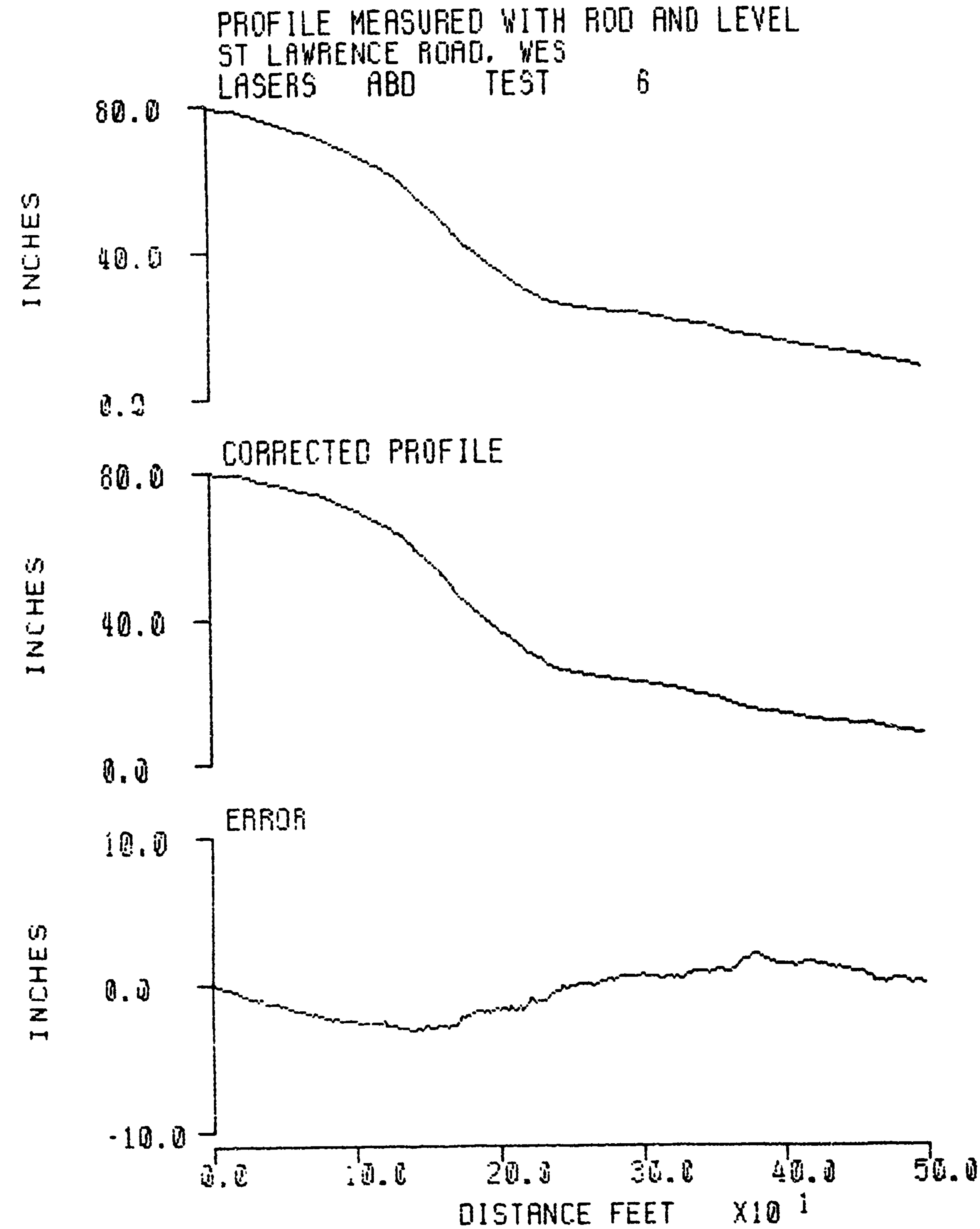
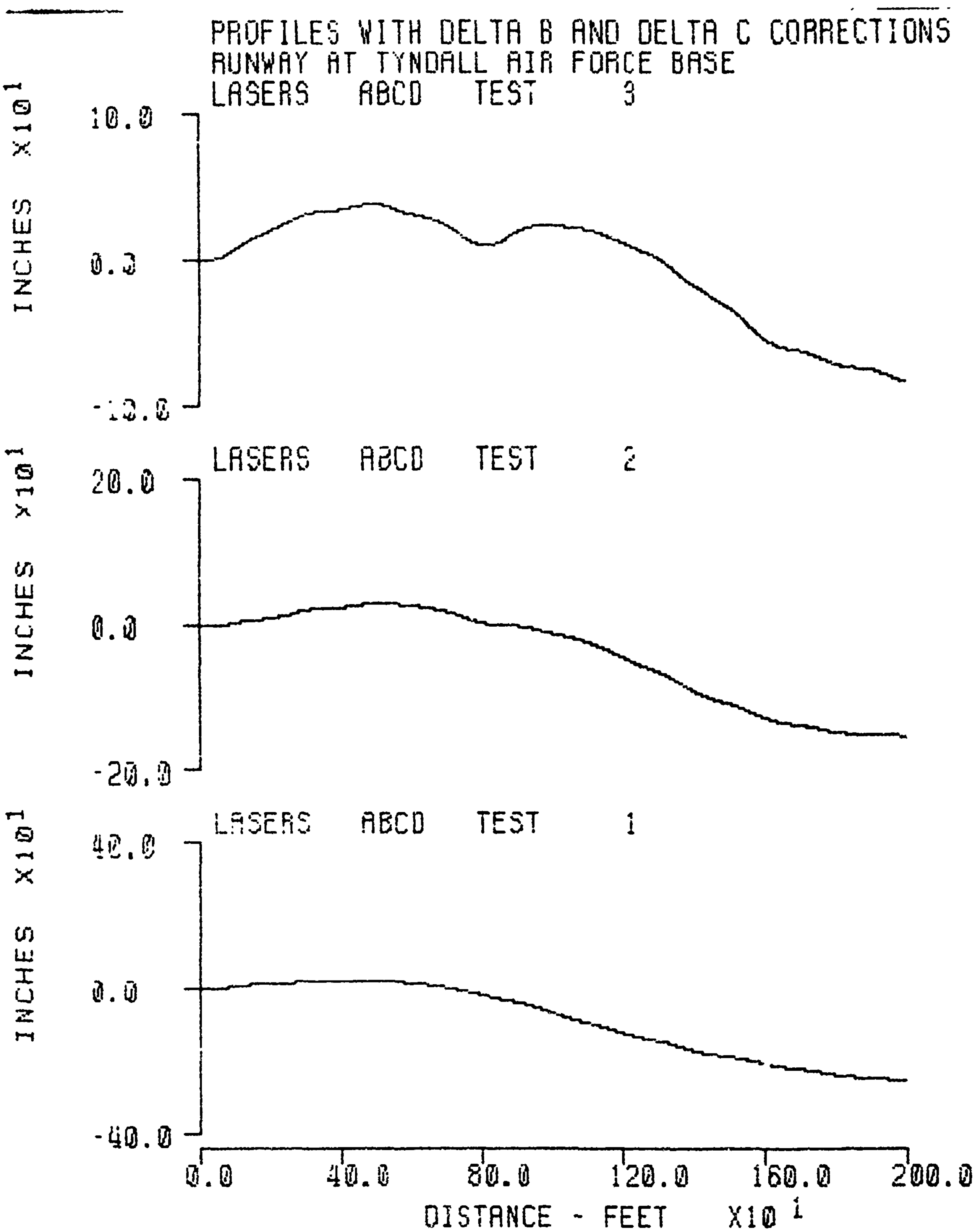
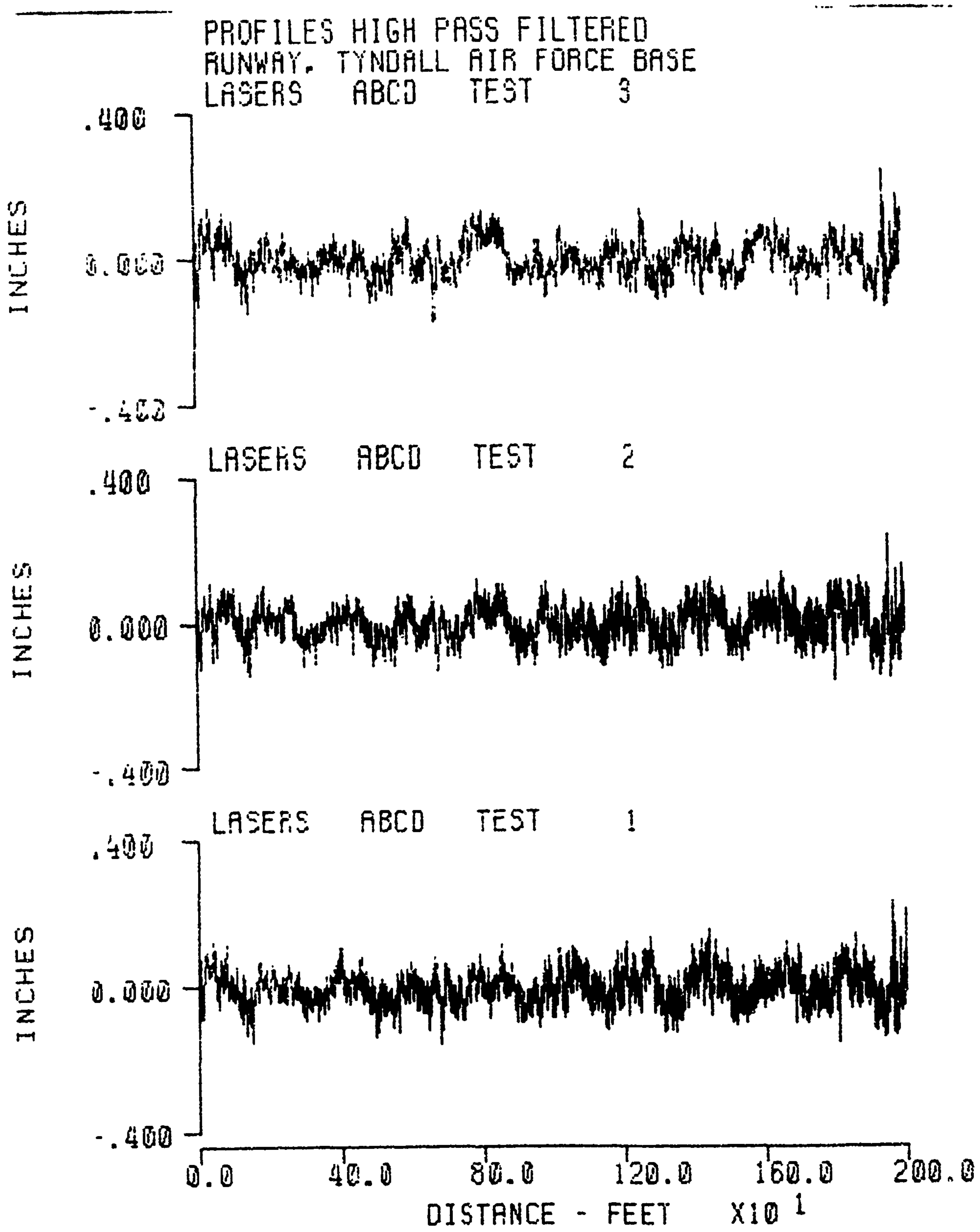
40.0
0.0
INCHES
CORRECTED PROFILE
80.0
40.0
0.0
INCHES
ERROR
10.0
0.0
-10.0
INCHES
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE FEET X10 1



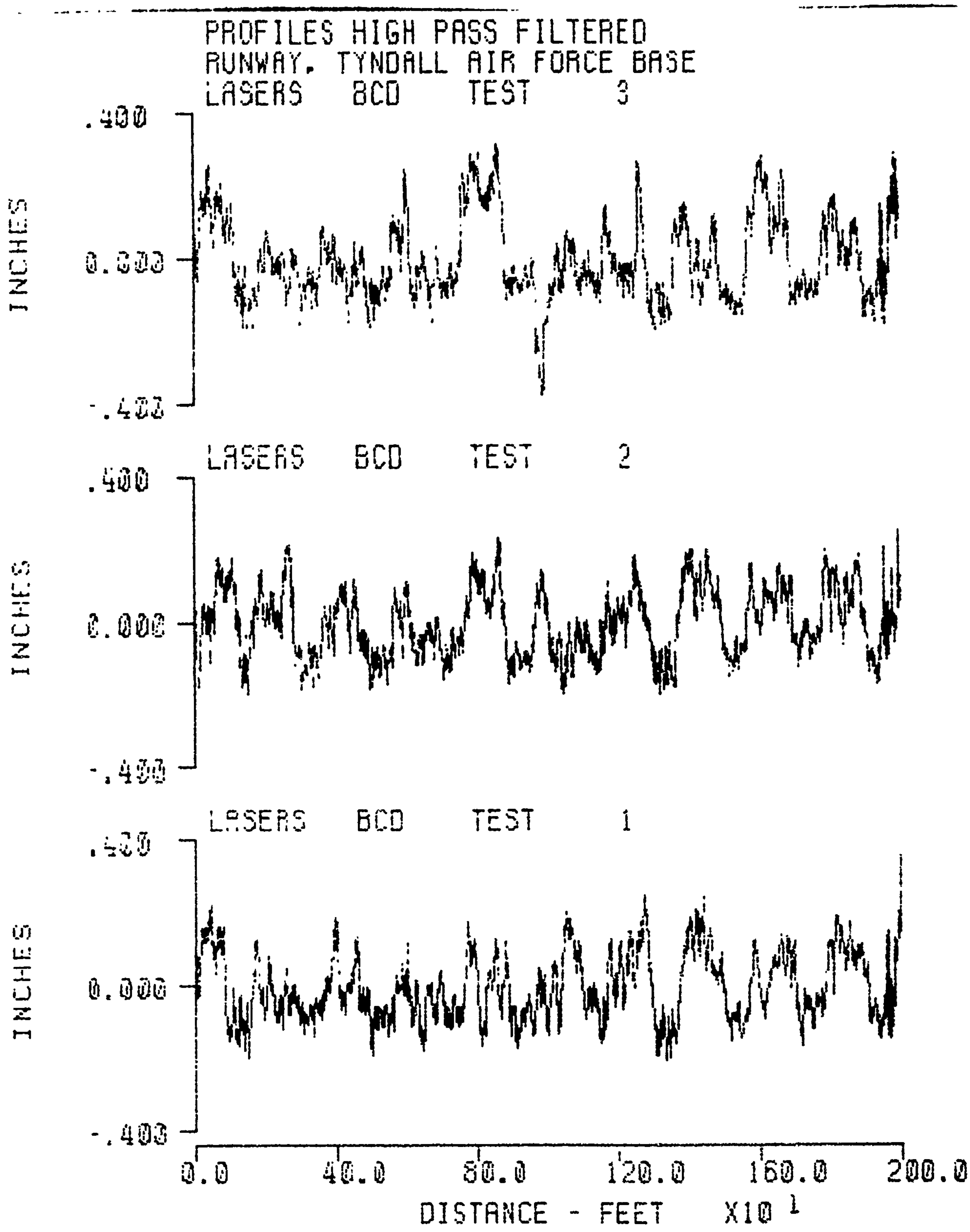
PROFILE MEASURED WITH ROD AND LEVEL
ST LAWRENCE ROAD, WES
LASERS ABD TEST 5
80.0
40.0
0.0
INCHES
CORRECTED PROFILE
80.0
40.0
0.0
INCHES
ERROR
10.0
0.0
-10.0
INCHES
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE FEET X10 1

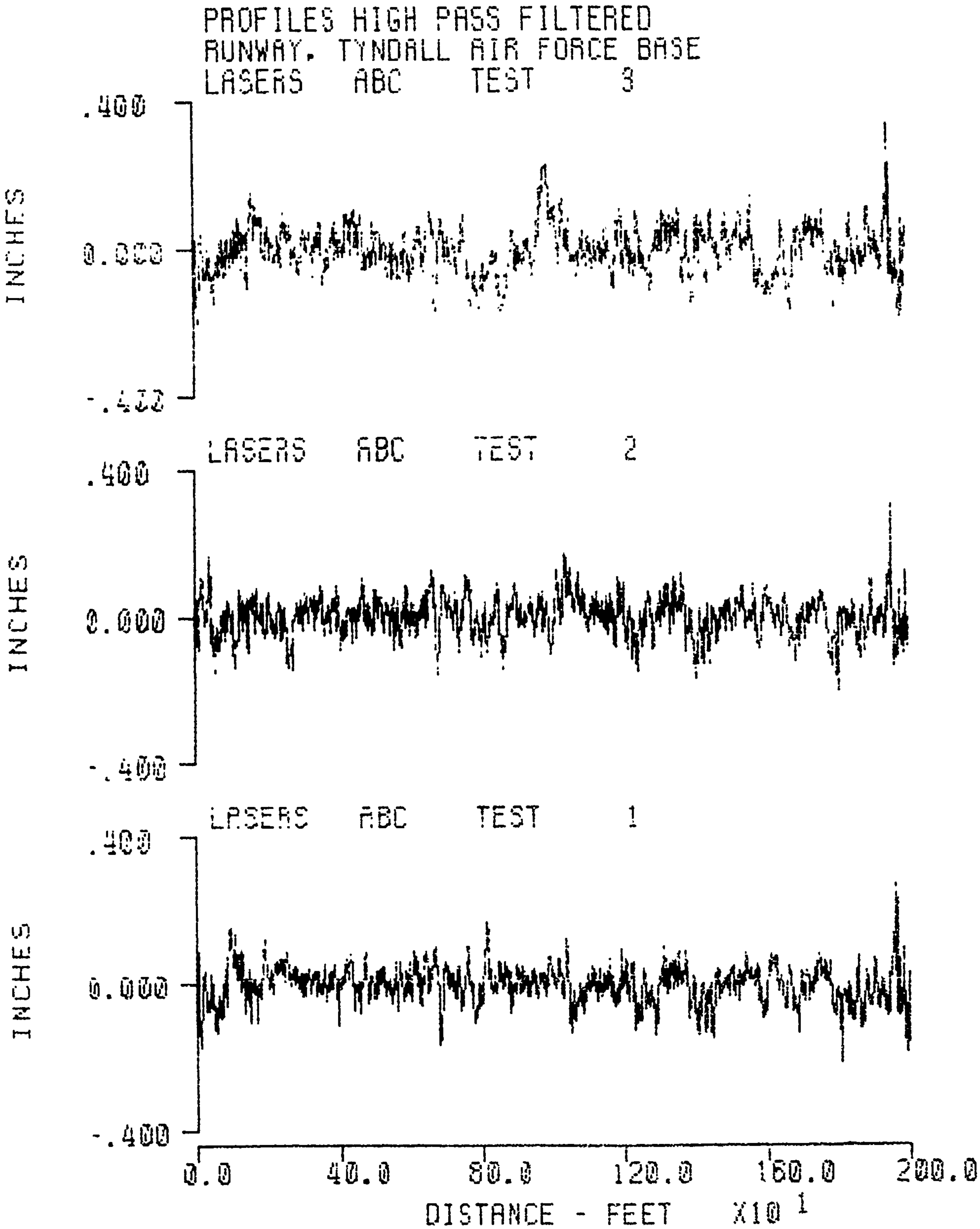

PROFILE MEASURED WITH ROD AND LEVEL
ST LAWRENCE ROAD, WES
LASERS ABD TEST 6
80.0
40.0
0.0
INCHES
CORRECTED PROFILE
80.0
40.0
0.0
INCHES
ERROR
10.0
0.0
-10.0
INCHES
0.0
10.0
20.0
30.0
40.0
50.0
DISTANCE FEET X10 1

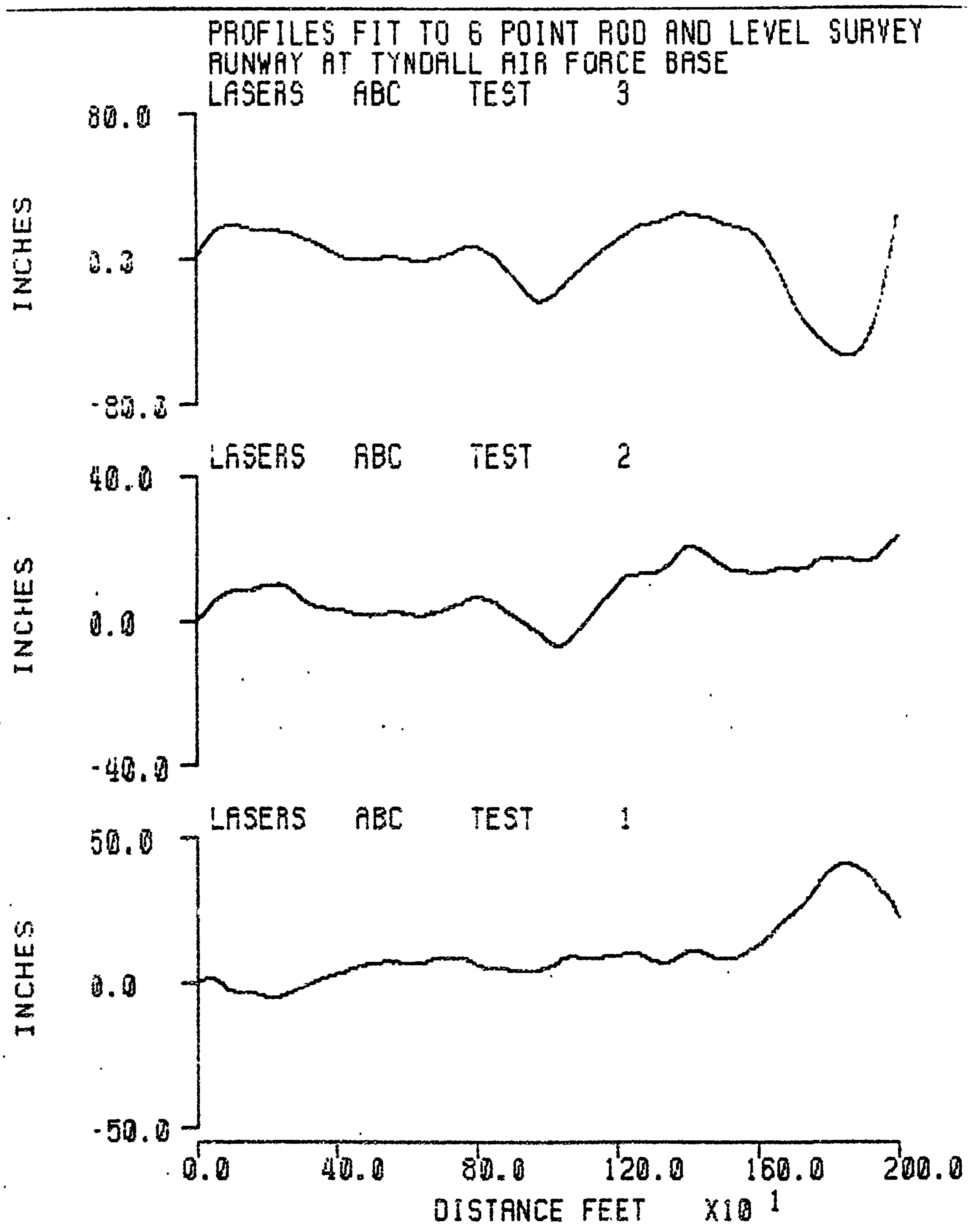

PROFILES WITH DELTA B AND DELTA C CORRECTIONS
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABCD TEST 3
LASERS ABCD TEST 2
LASERS ABCD TEST 1
INCHES X10
10.0
-10.0
20.0
0.0
-20.0
40.0
-40.0
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE - FEET X10

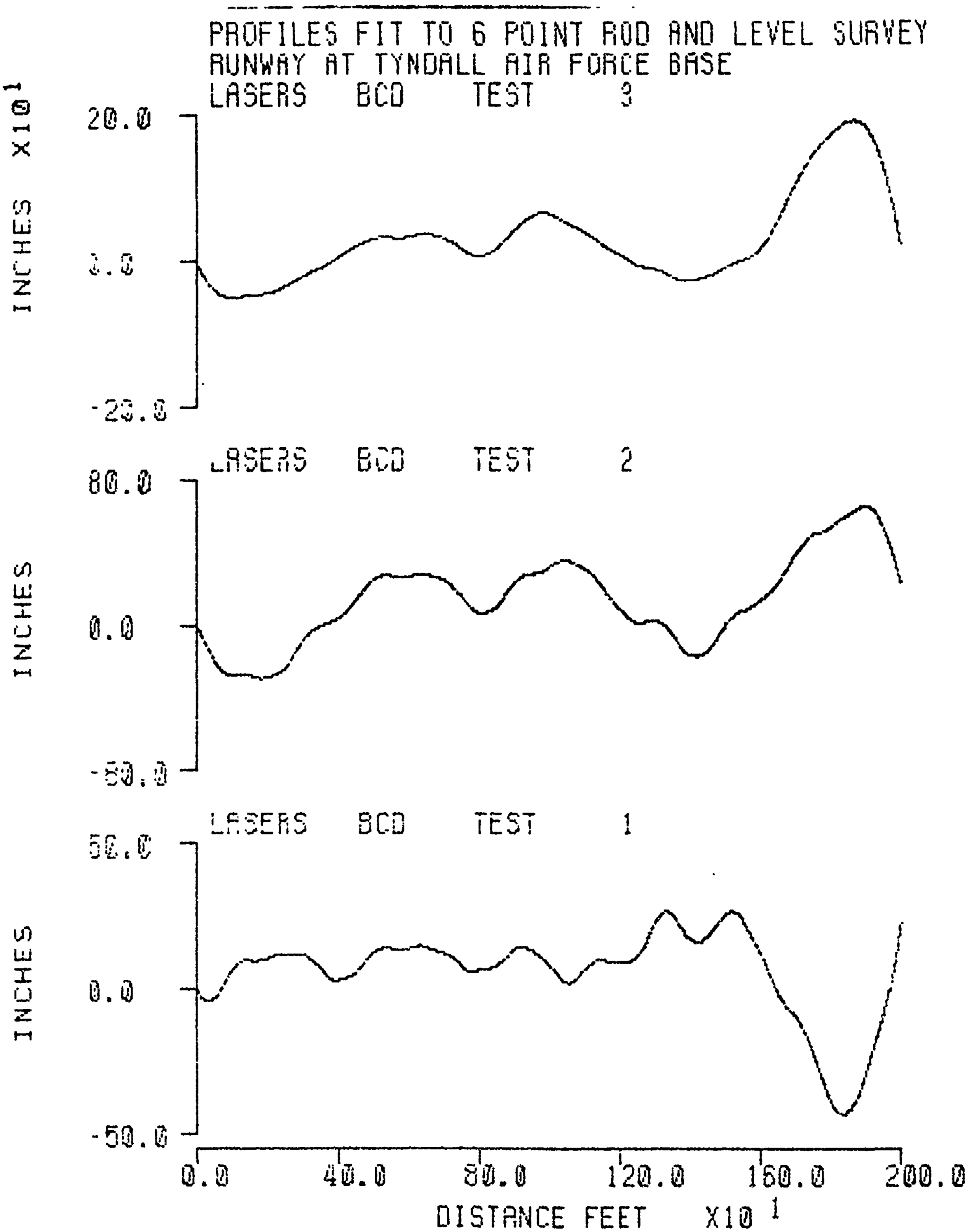


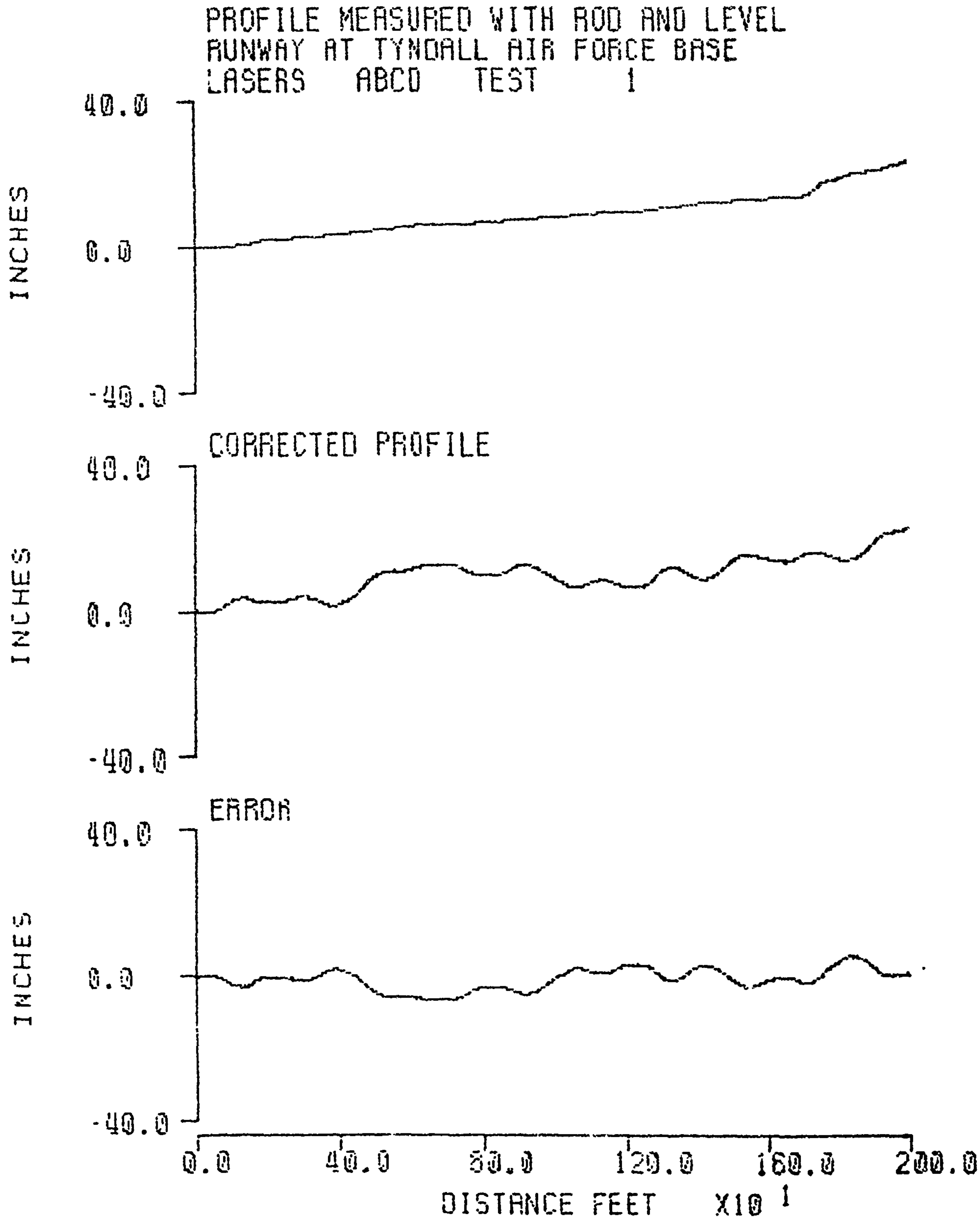
PROFILES HIGH PASS FILTERED
RUNWAY, TYNDALL AIR FORCE BASE
LASERS ABCD TEST 3
.400
0.000
-.400
INCHES
LASERS ABCD TEST 2
.400
0.000
-.400
INCHES
LASERS ABCD TEST 1
.400
0.000
-.400
INCHES
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE - FEET X10 1


PROFILES HIGH PASS FILTERED
RUNWAY, TYNDALL AIR FORCE BASE
LASERS BCD TEST 3
.400
0.000
-.400
INCHES
LASERS BCD TEST 2
.400
0.000
-.400
INCHES
LASERS BCD TEST 1
.400
0.000
-.400
INCHES
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE - FEET X10 1

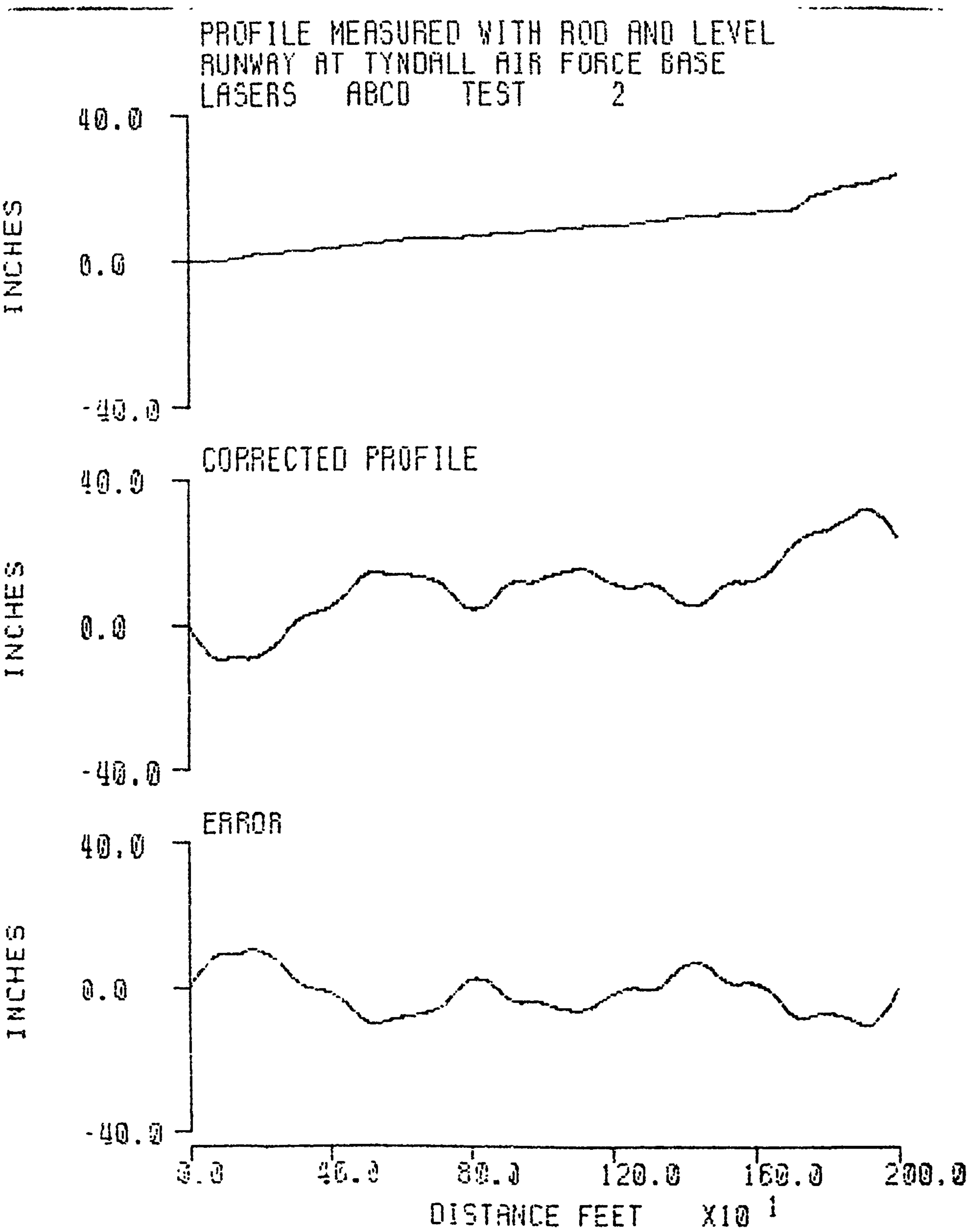

PROFILES HIGH PASS FILTERED
RUNWAY, TYNDALL AIR FORCE BASE
LASERS ABC TEST 3
.400
0.000
-.400
INCHES
LASERS ABC TEST 2
.400
0.000
-.400
INCHES
LASERS ABC TEST 1
.400
0.000
-.400
INCHES
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE - FEET X10 1

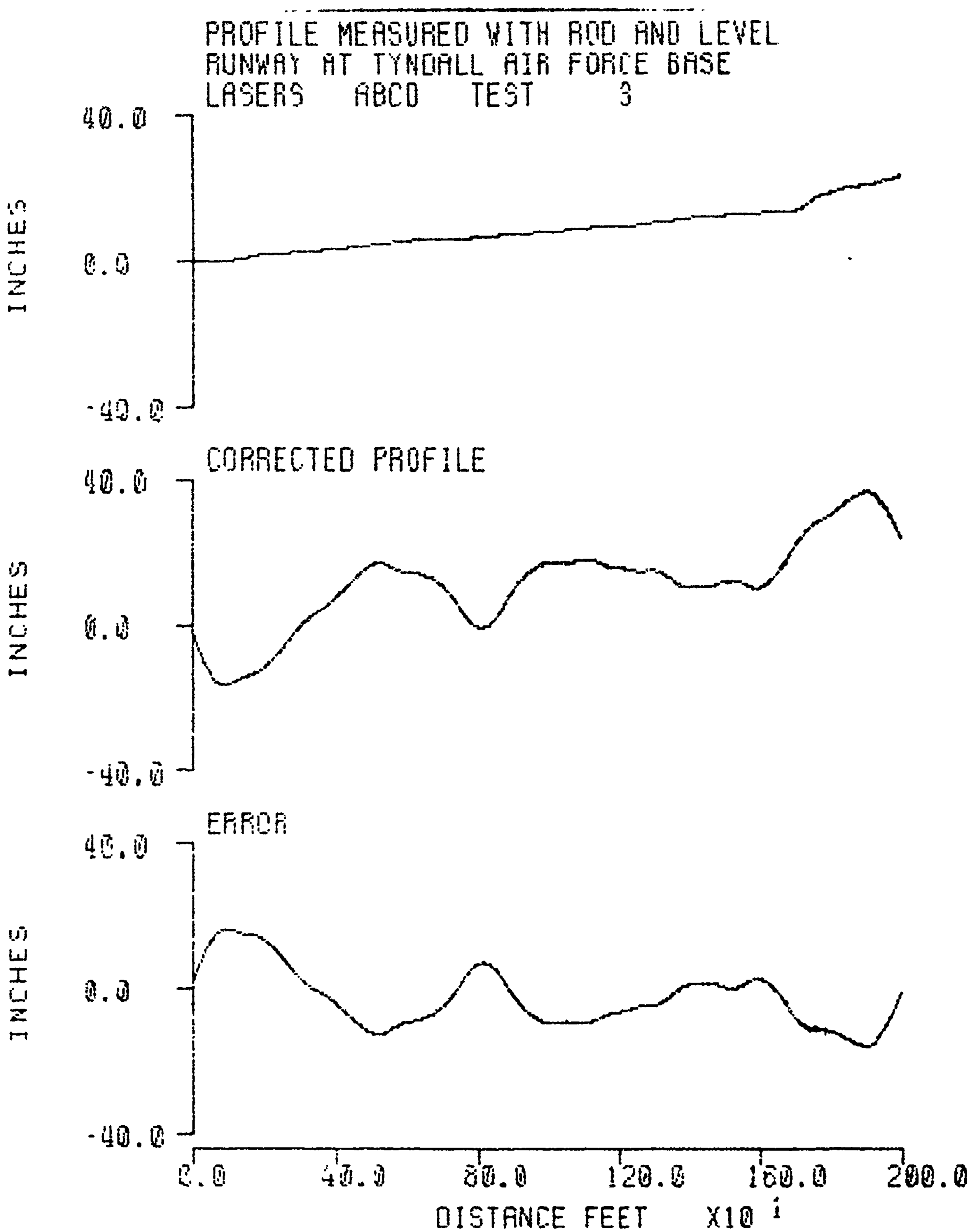

PROFILES FIT TO 6 POINT ROD AND LEVEL SURVEY
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABC TEST 3
80.0
0.0
-80.0
INCHES
LASERS ABC TEST 2
40.0
0.0
-40.0
INCHES
LASERS ABC TEST 1
50.0
0.0
-50.0
INCHES
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE FEET X10 1

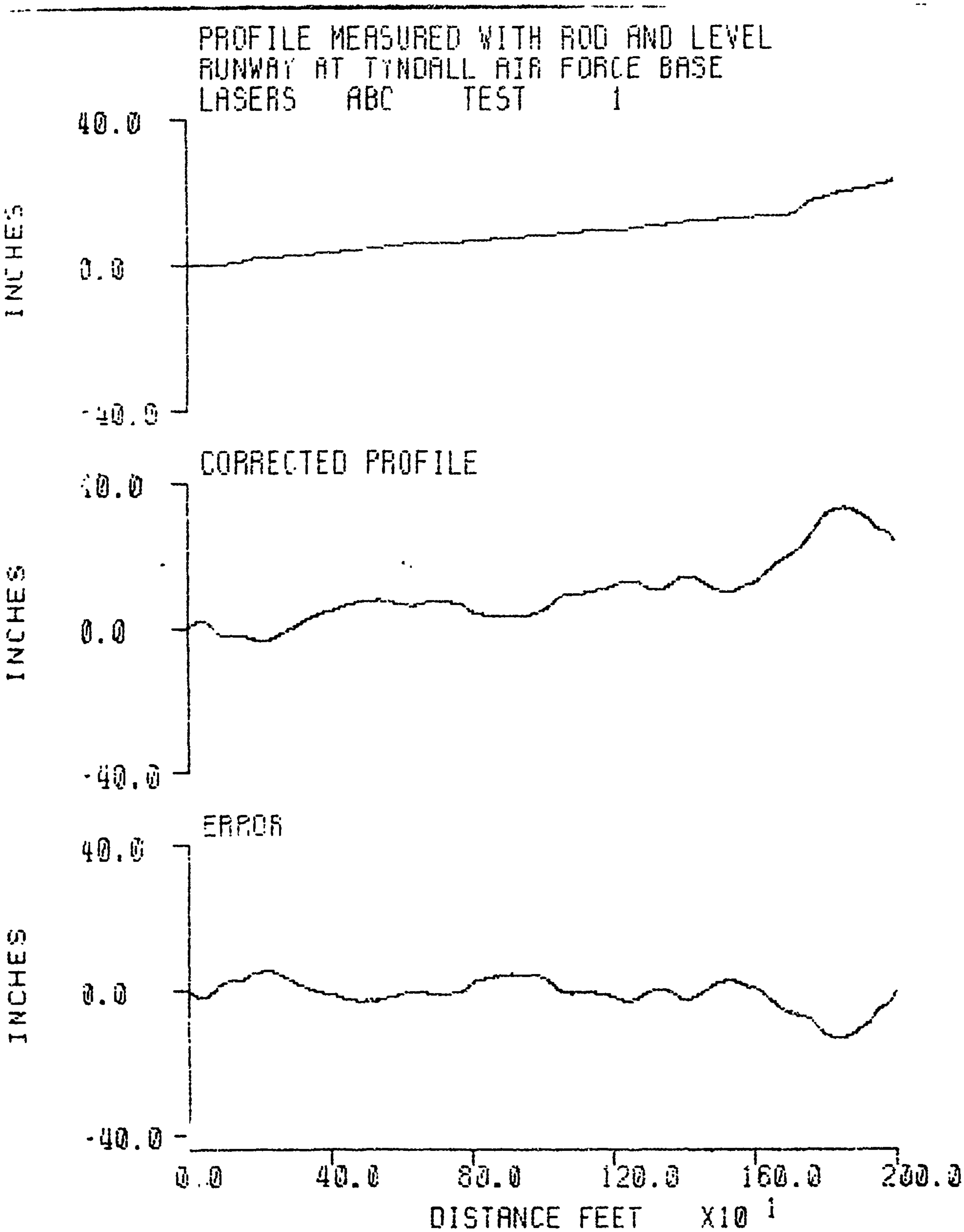

PROFILES FIT TO 6 POINT ROD AND LEVEL SURVEY
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS BCD TEST 3
INCHES X10 1
20.0
0.0
-20.0
LASERS BCD TEST 2
INCHES
80.0
0.0
-80.0
LASERS BCD TEST 1
INCHES
50.0
0.0
-50.0
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE FEET X10 1

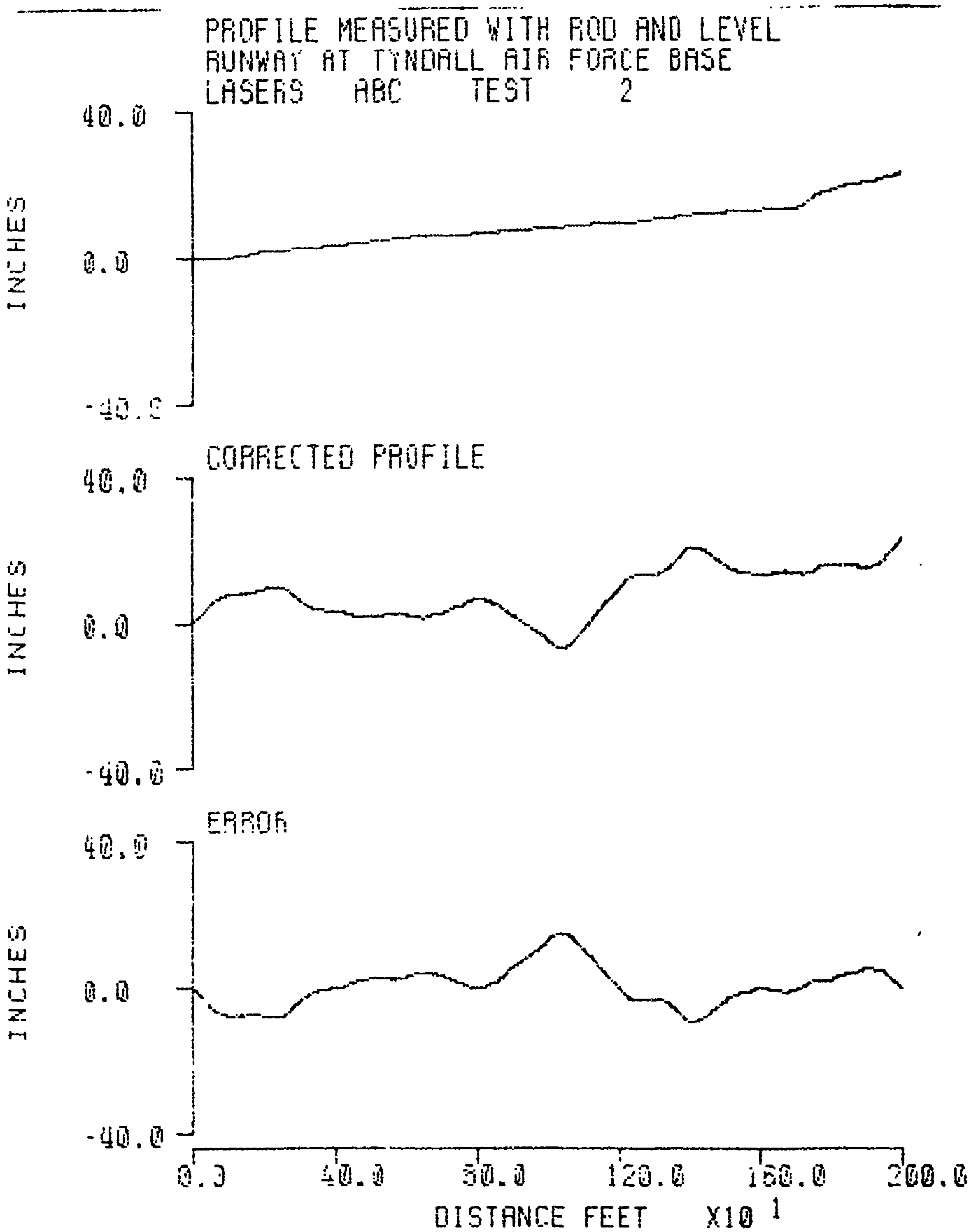


PROFILE MEASURED WITH ROD AND LEVEL
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABCD TEST 1
40.0
0.0
-40.0
INCHES
CORRECTED PROFILE
40.0
0.0
-40.0
INCHES
ERROR
40.0
0.0
-40.0
INCHES
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE FEET X10 1


PROFILE MEASURED WITH ROD AND LEVEL
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABCD TEST 2
40.0
INCHES
0.0
-40.0
CORRECTED PROFILE
40.0
INCHES
0.0
-40.0
ERROR
40.0
INCHES
0.0
-40.0
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE FEET X10 1


PROFILE MEASURED WITH ROD AND LEVEL
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABCD TEST 3
40.0
0.0
-40.0
INCHES
CORRECTED PROFILE
40.0
0.0
-40.0
INCHES
ERROR
40.0
0.0
-40.0
INCHES
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE FEET X10 1


PROFILE MEASURED WITH ROD AND LEVEL
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABC TEST 1
40.0
0.0
-40.0
INCHES
CORRECTED PROFILE
40.0
0.0
-40.0
INCHES
ERROR
40.0
0.0
-40.0
INCHES
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE FEET X10 1


PROFILE MEASURED WITH ROD AND LEVEL
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABC TEST 2
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-40.0
INCHES
CORRECTED PROFILE
40.0
0.0
-40.0
INCHES
ERROR
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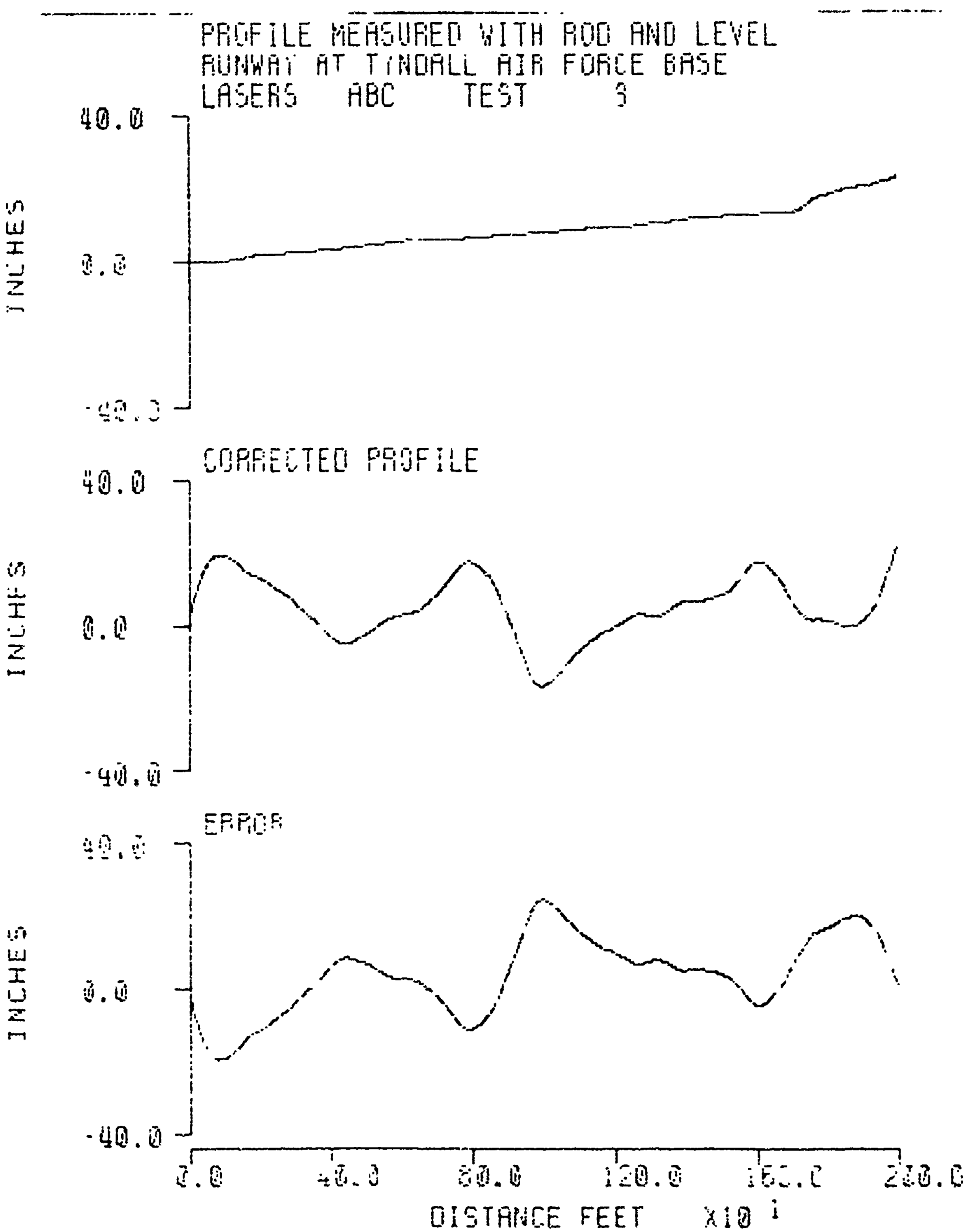
0.0
-40.0
INCHES
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE FEET X10 1



PROFILE MEASURED WITH ROD AND LEVEL
RUNWAY AT TINDALL AIR FORCE BASE
LASERS ABC TEST 9
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-40.0
INCHES
CORRECTED PROFILE
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-40.0
INCHES
ERROR
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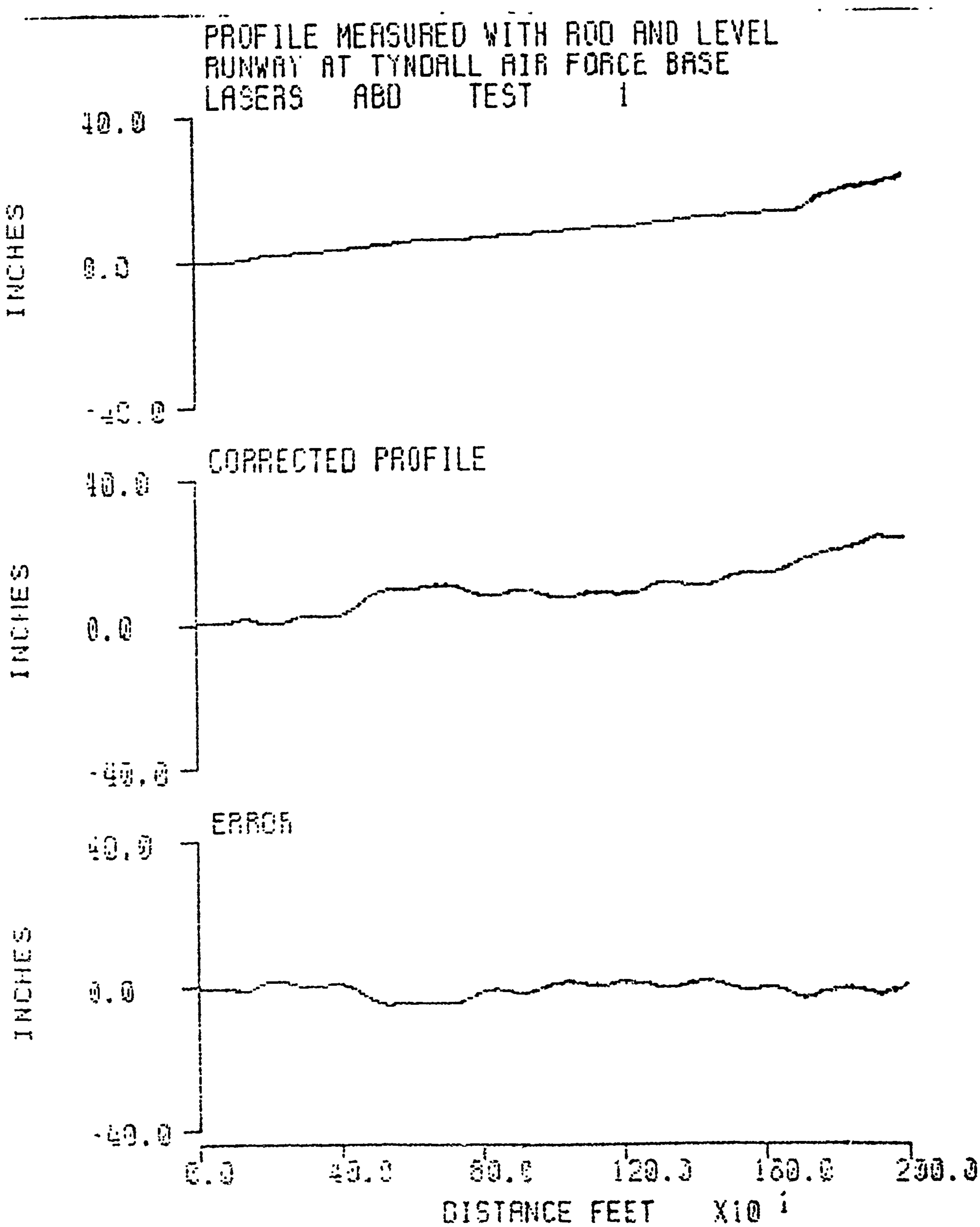
INCHES
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE FEET X10 1


PROFILE MEASURED WITH ROD AND LEVEL
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABD TEST 1
40.0
INCHES
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-40.0
CORRECTED PROFILE
40.0
INCHES
0.0
-40.0
ERROR
40.0
INCHES
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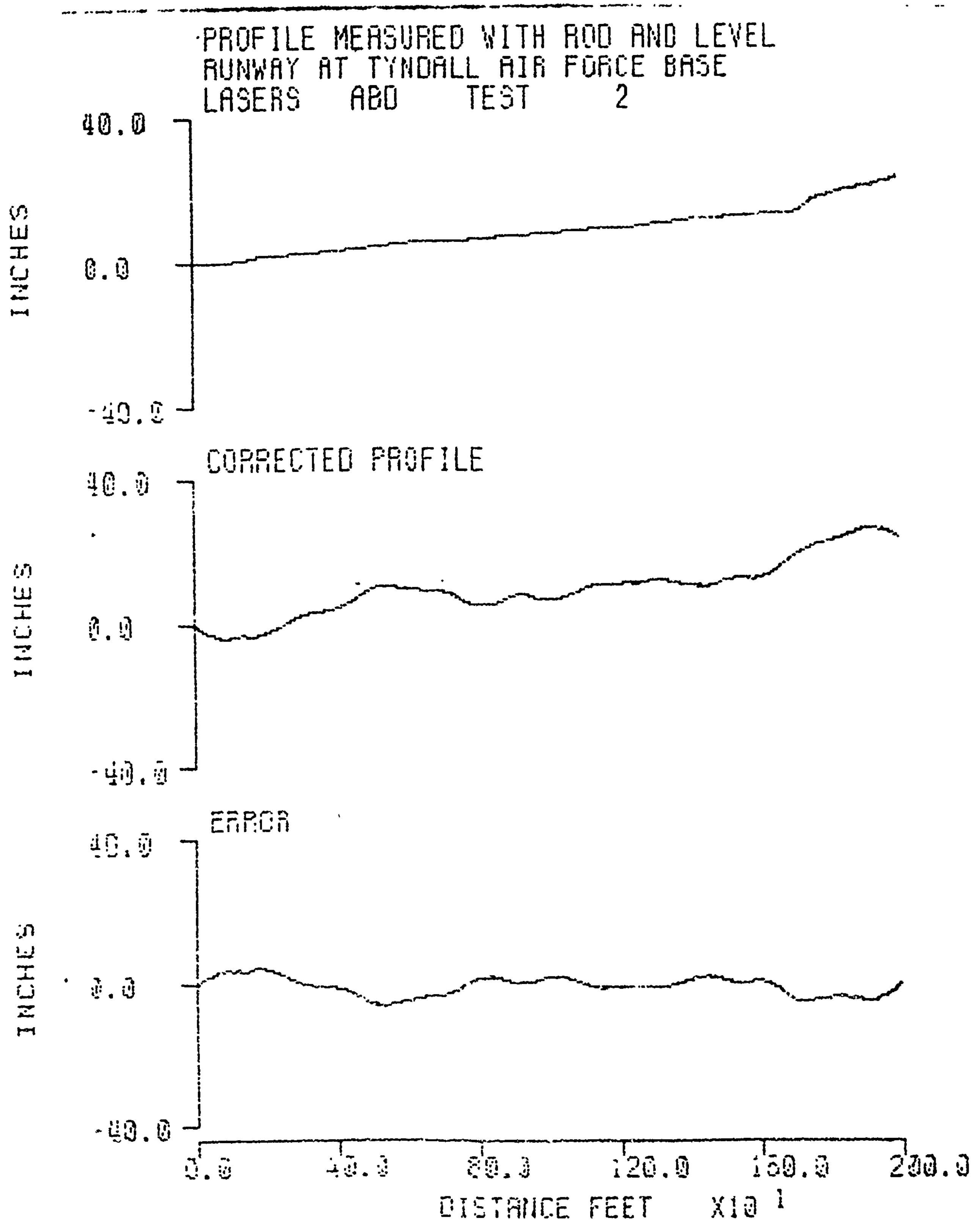
-40.0
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE FEET X10 1


PROFILE MEASURED WITH ROD AND LEVEL
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABD TEST 2
40.0
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-40.0
INCHES
CORRECTED PROFILE
40.0
0.0
-40.0
INCHES
ERROR
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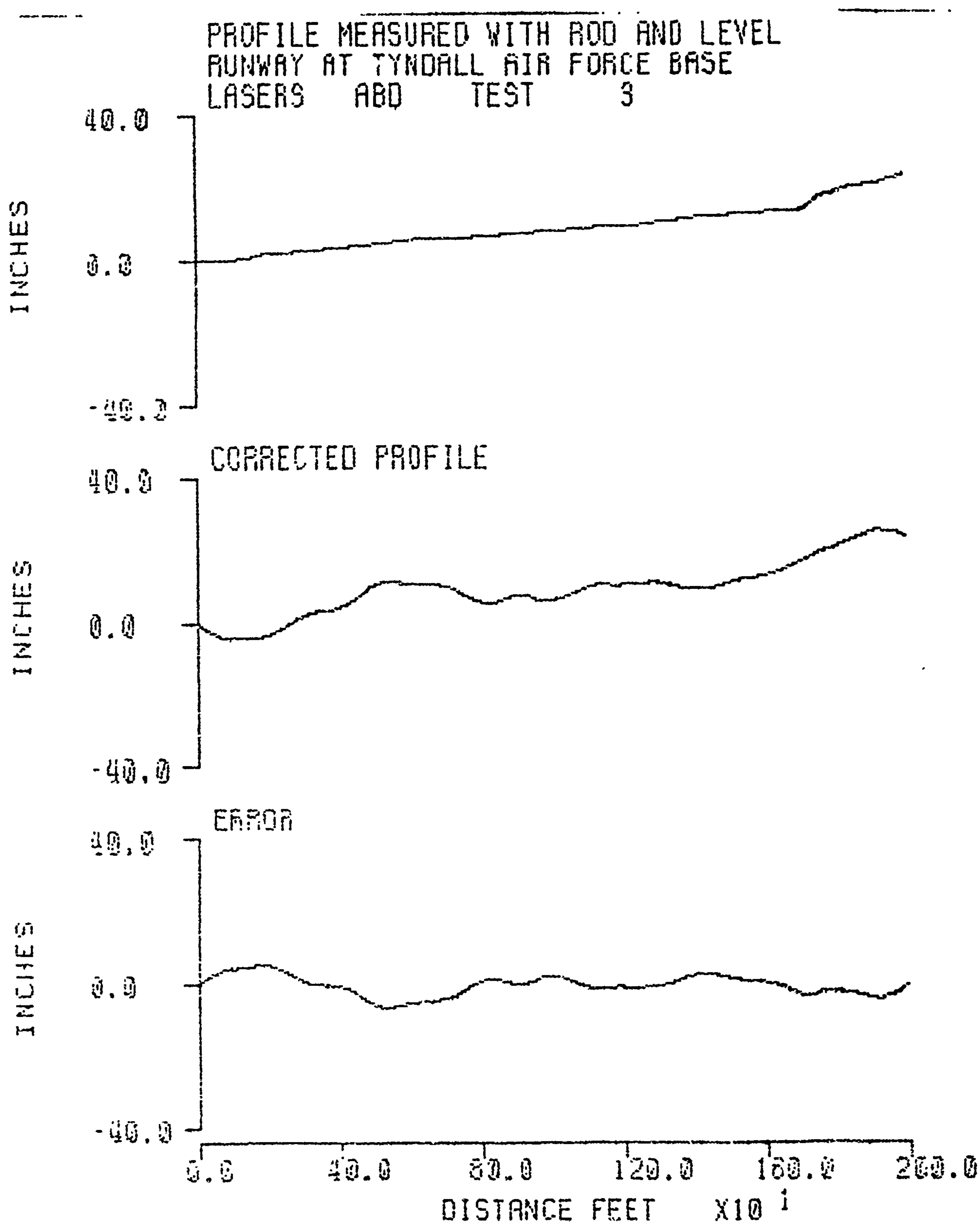
INCHES
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE FEET X10 1


PROFILE MEASURED WITH ROD AND LEVEL
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABD TEST 3
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-40.0
INCHES
CORRECTED PROFILE
40.0
0.0
-40.0
INCHES
ERROR
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INCHES
0.0
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120.0
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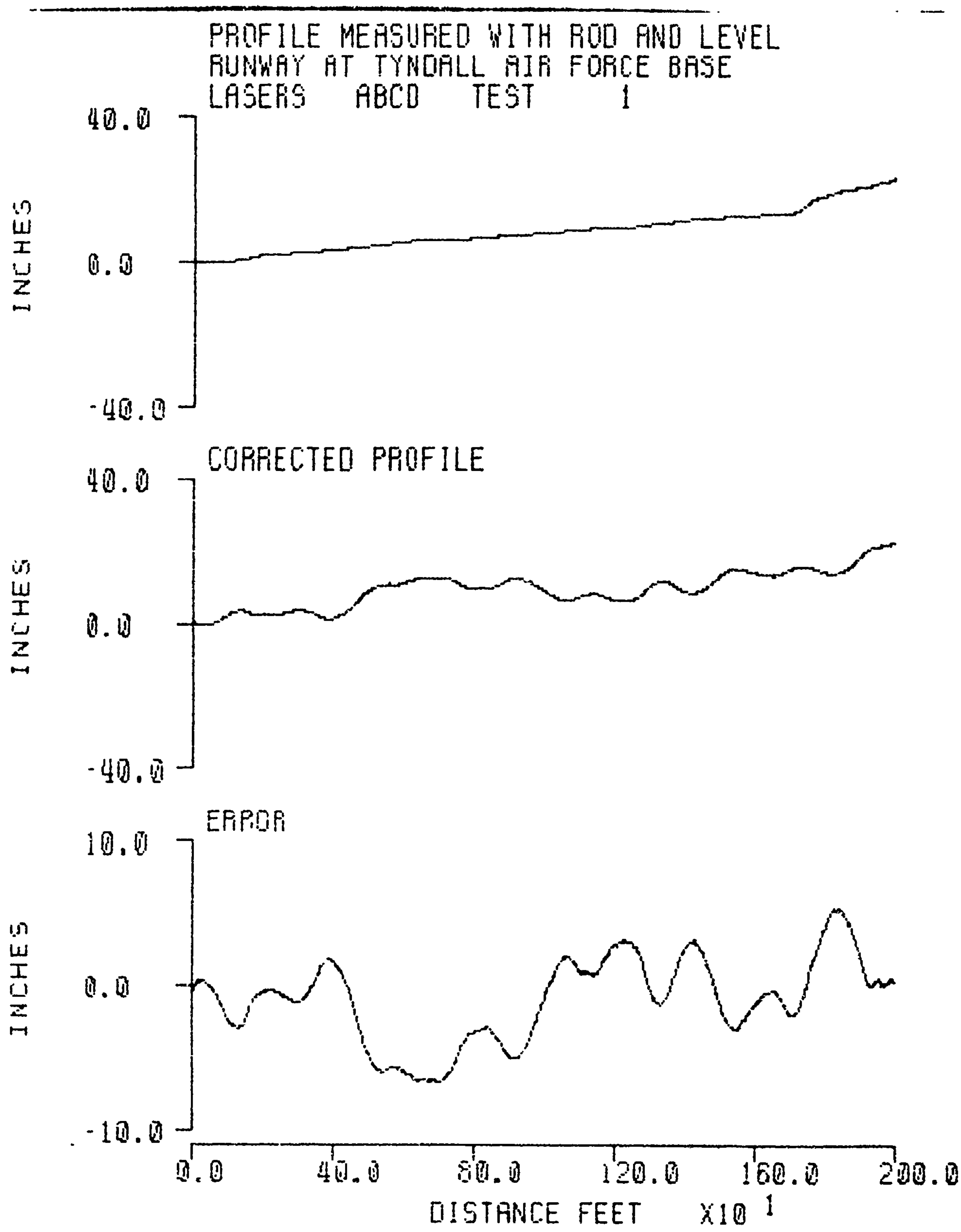
200.0
DISTANCE FEET X10 1



PROFILE MEASURED WITH ROD AND LEVEL
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABCD TEST 1
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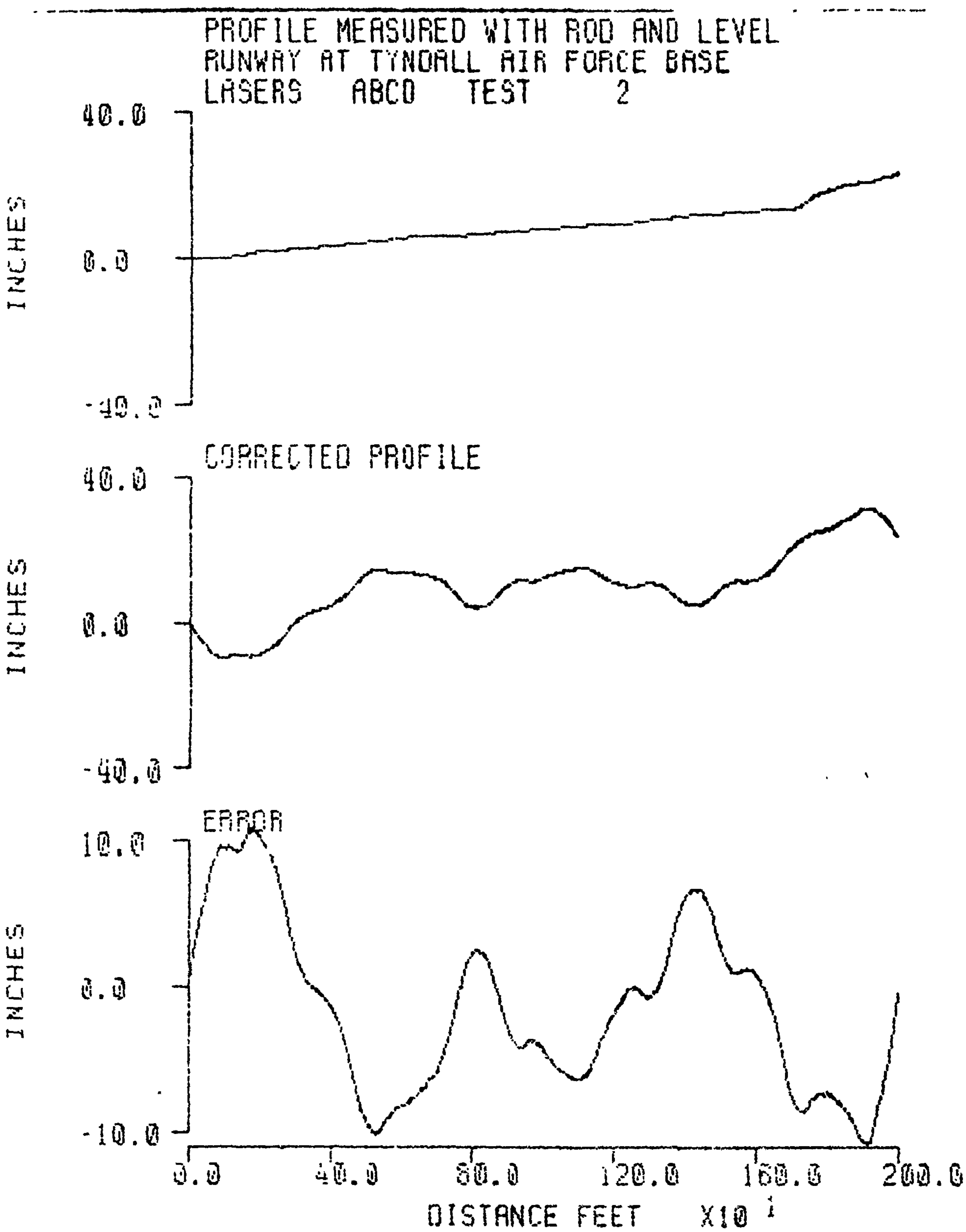
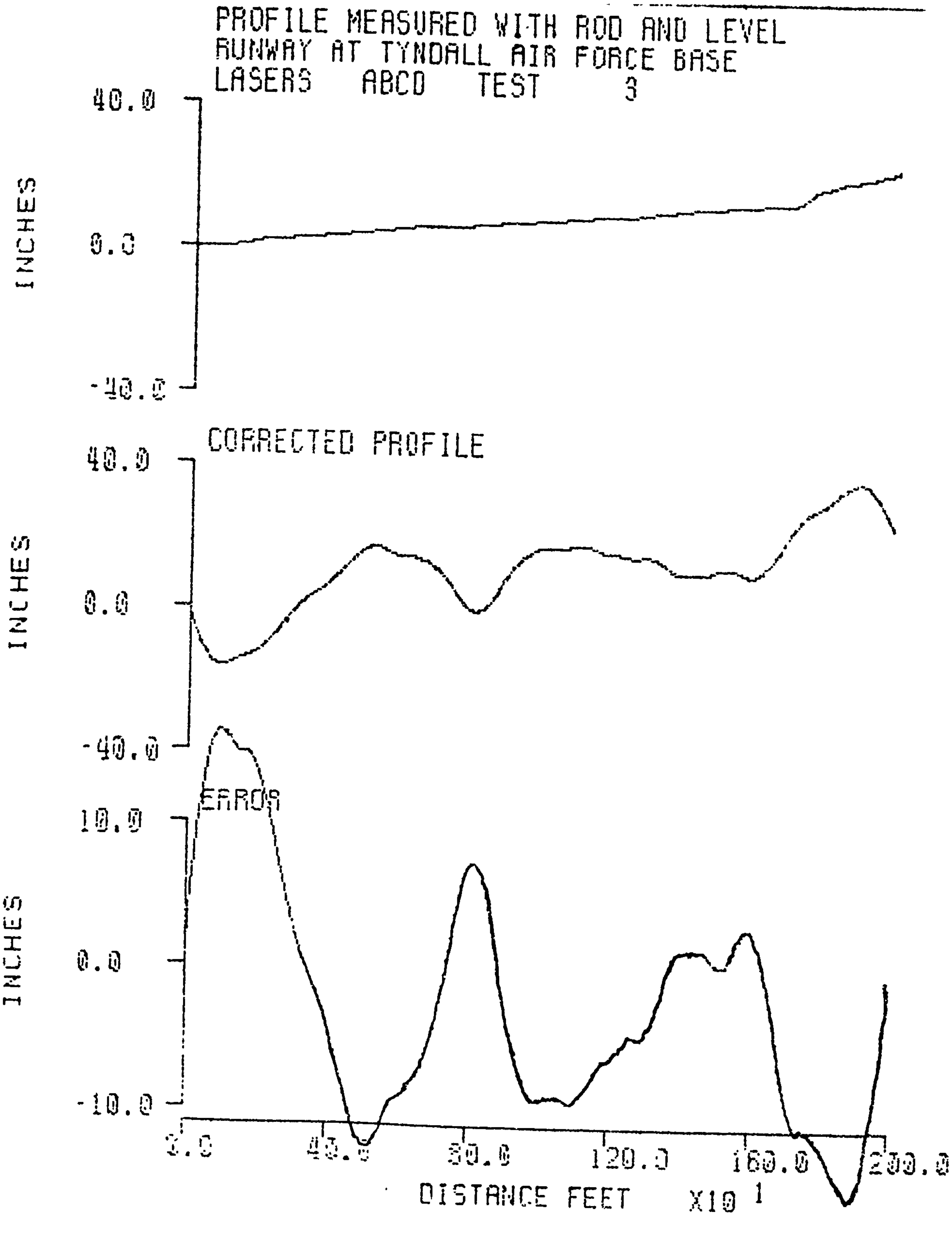
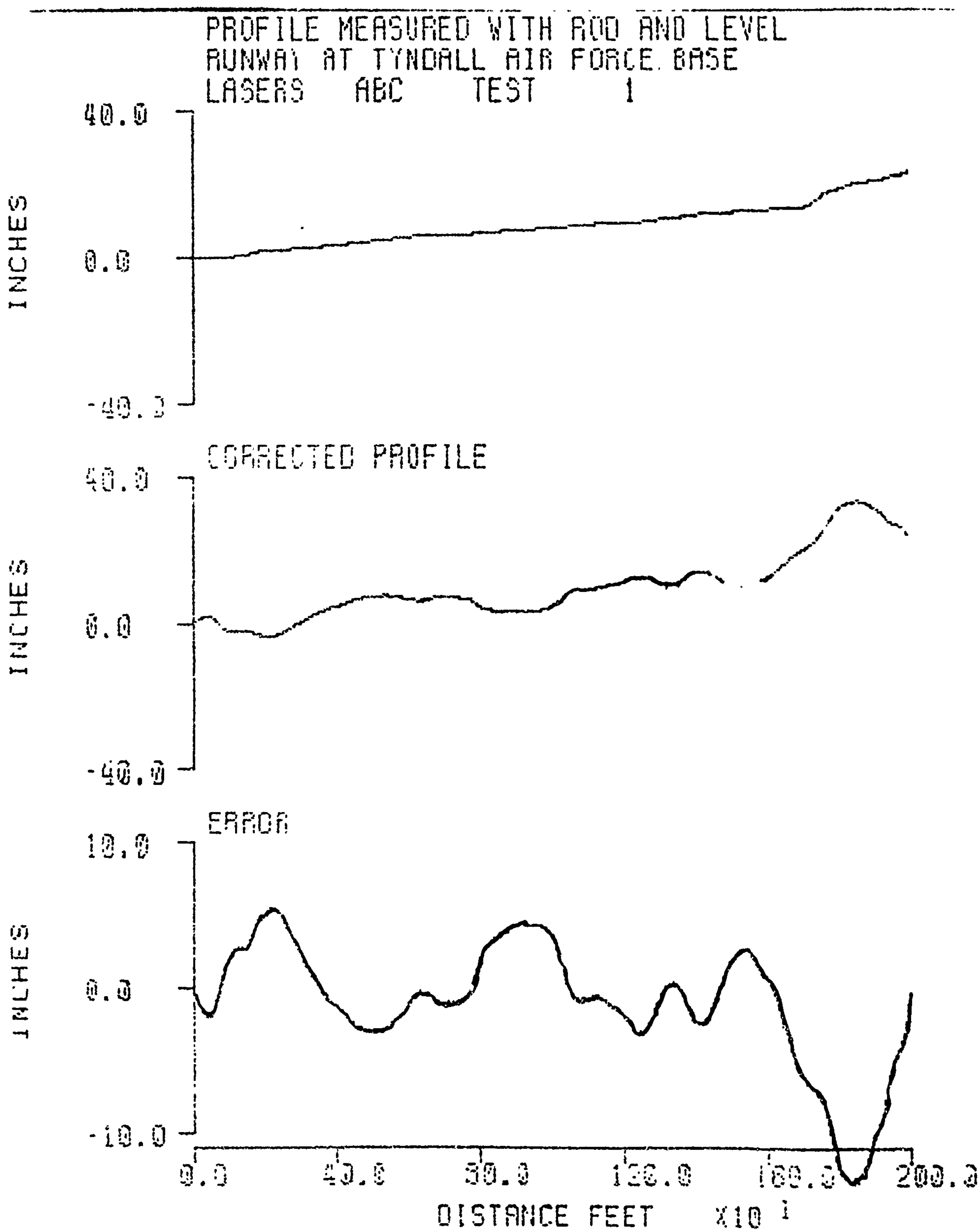
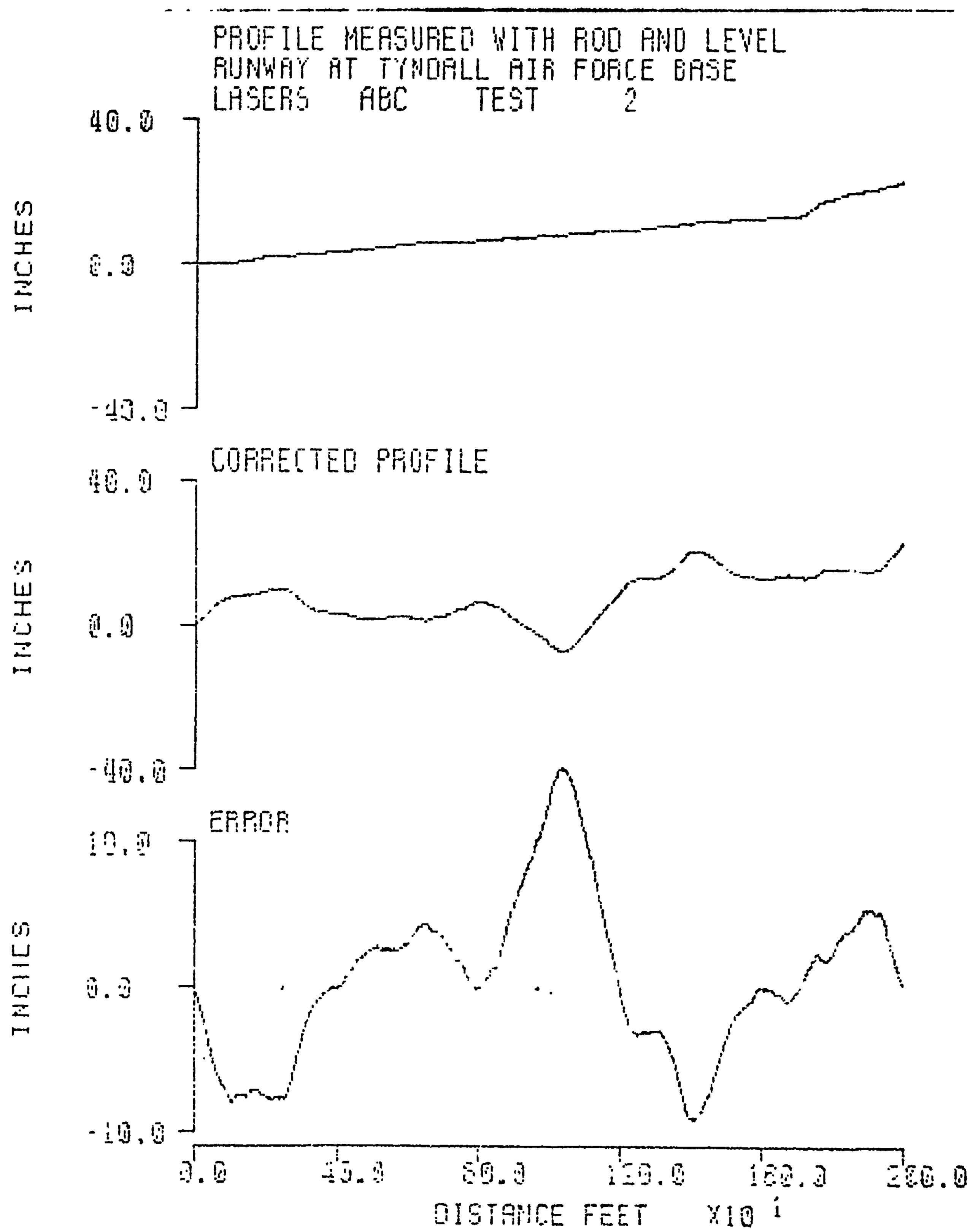
0.0
-40.0
INCHES
CORRECTED PROFILE
40.0
0.0
-40.0
INCHES
ERROR
10.0
0.0
-10.0
INCHES
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE FEET X10 1

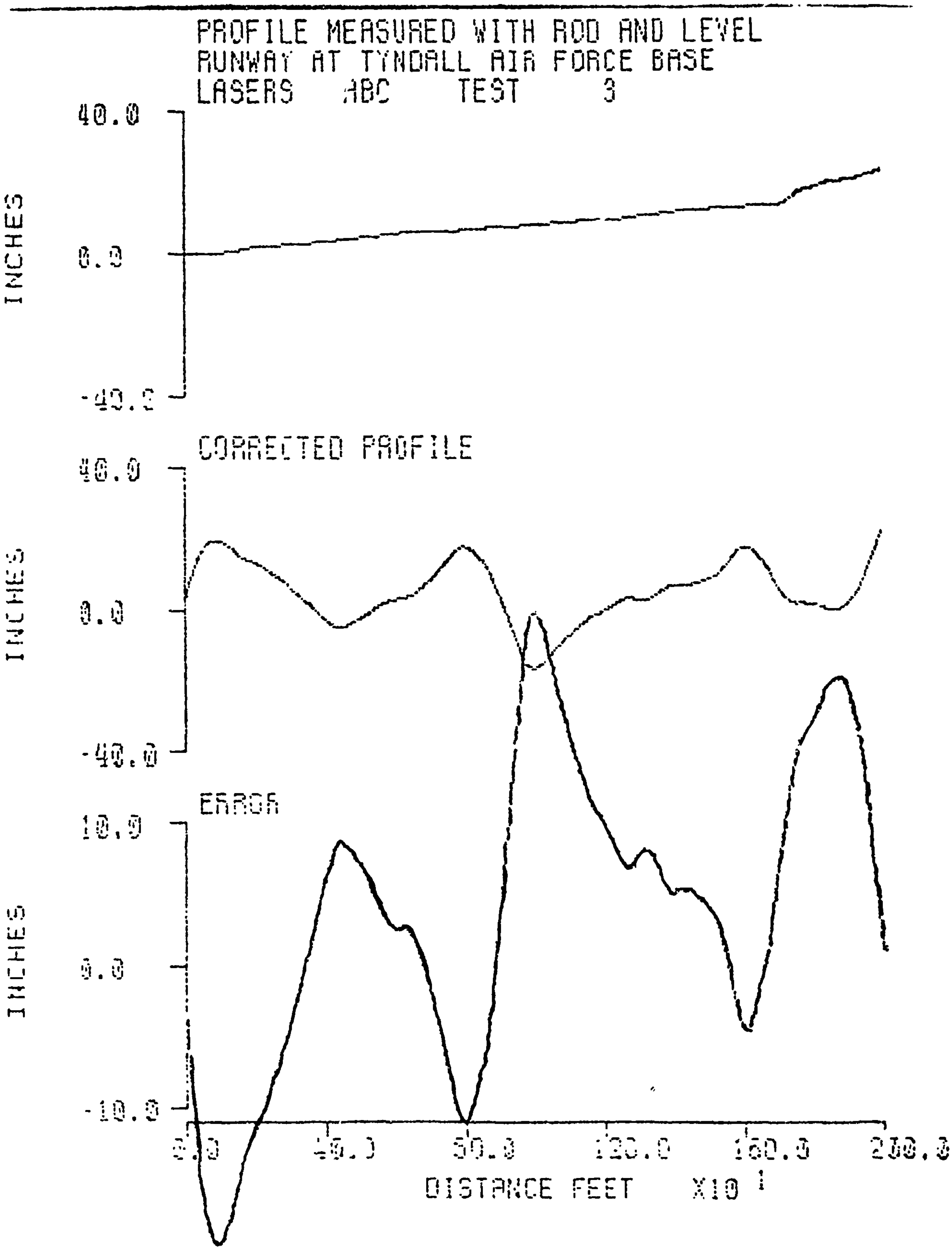


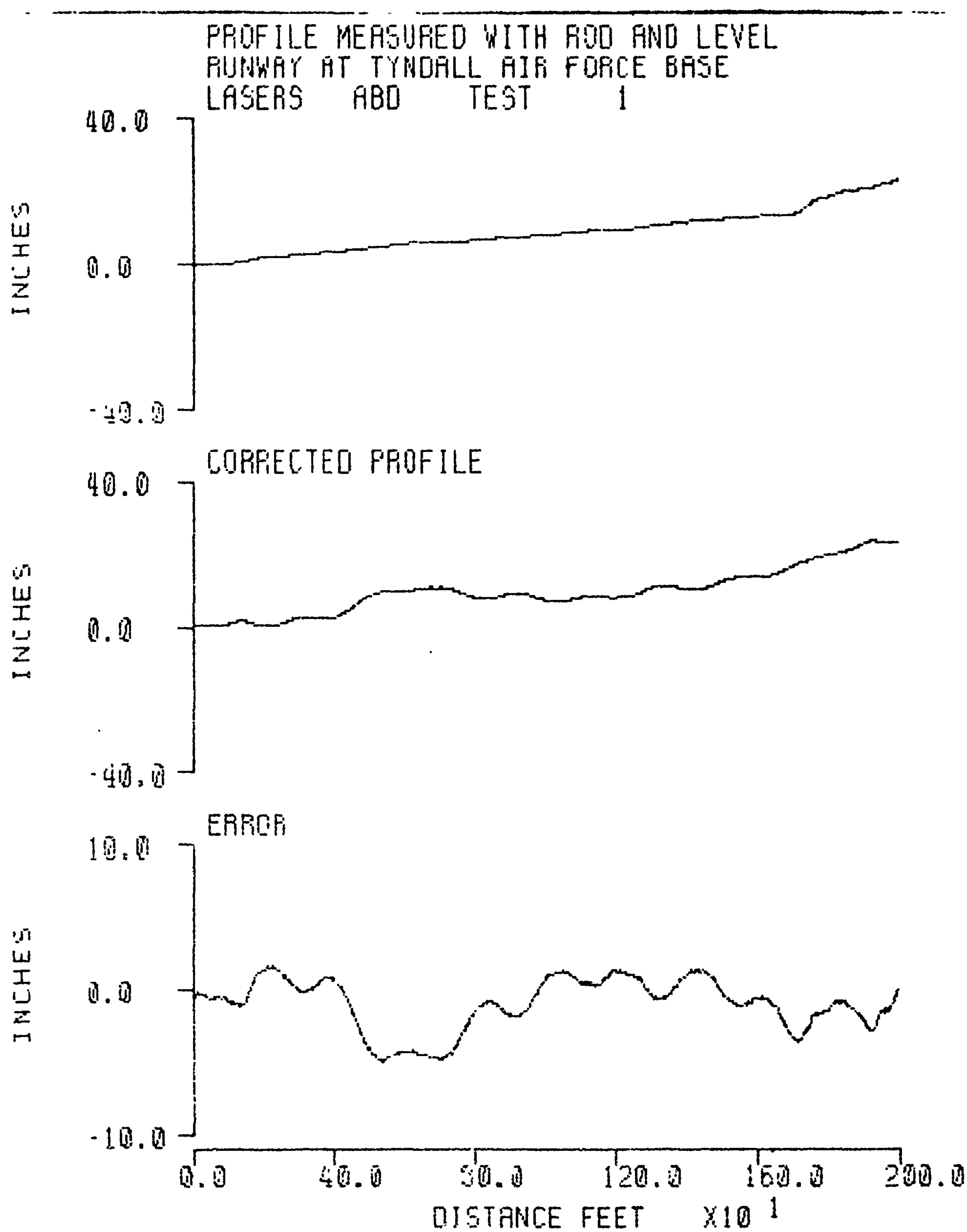
PROFILE MEASURED WITH ROD AND LEVEL
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABCD TEST 2
40.0
0.0
-40.0
INCHES
CORRECTED PROFILE
40.0
0.0
-40.0
INCHES
ERROR
10.0
0.0
-10.0
INCHES
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE FEET X10 1

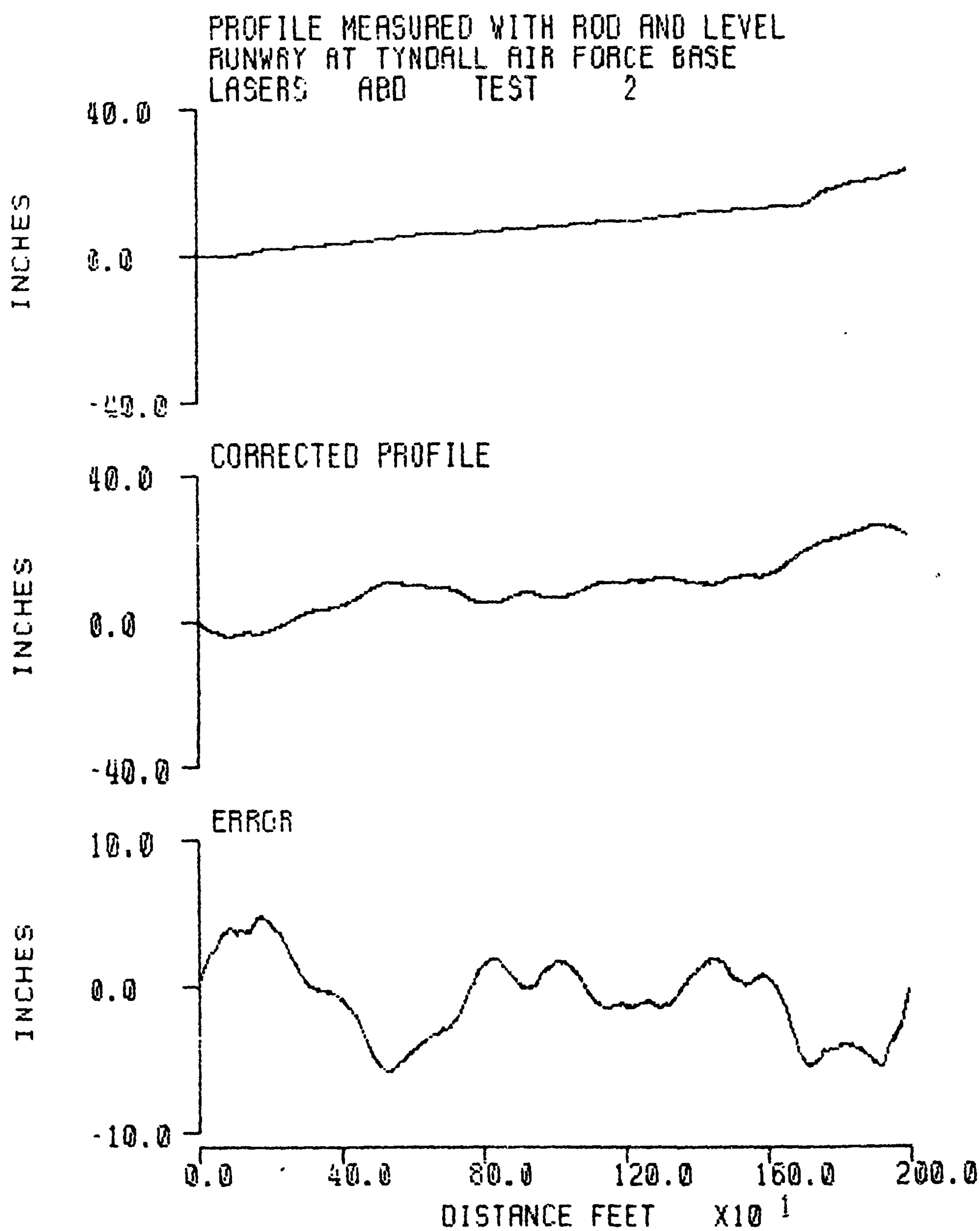

PROFILE MEASURED WITH ROD AND LEVEL
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABCD TEST 3
40.0
0.0
-40.0
INCHES
CORRECTED PROFILE
40.0
0.0
-40.0
INCHES
ERROR
10.0
0.0
-10.0
INCHES
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE FEET X10 1


PROFILE MEASURED WITH ROD AND LEVEL
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABC TEST 1
40.0
0.0
-40.0
INCHES
CORRECTED PROFILE
40.0
0.0
-40.0
INCHES
ERROR
10.0
0.0
-10.0
INCHES
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE FEET X10 1

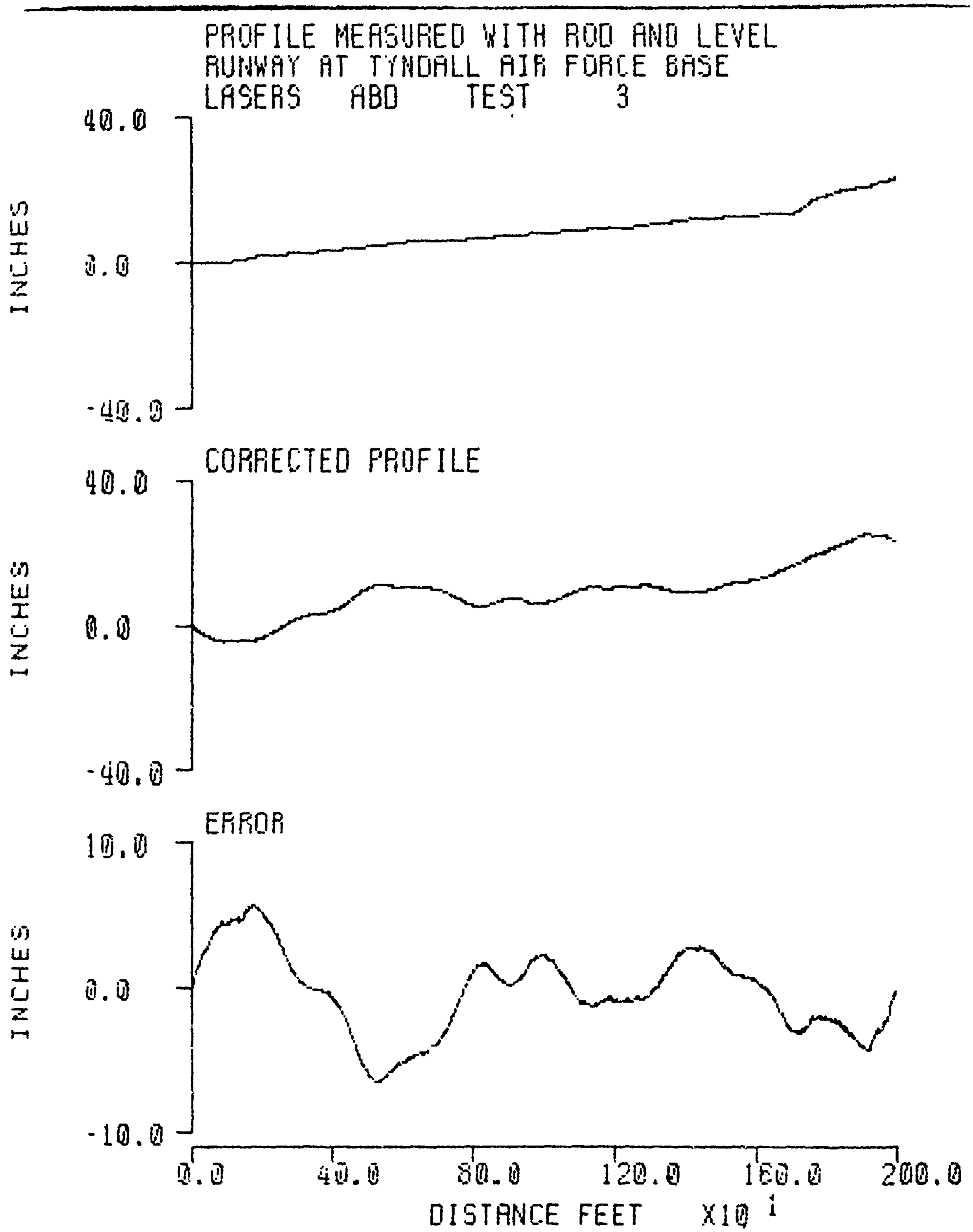

PROFILE MEASURED WITH ROD AND LEVEL
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABC TEST 2
40.0
0.0
-40.0
INCHES
CORRECTED PROFILE
40.0
0.0
-40.0
INCHES
ERROR
10.0
0.0
-10.0
INCHES
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE FEET X10 1


PROFILE MEASURED WITH ROD AND LEVEL
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABC TEST 3
40.0
0.0
-40.0
INCHES
CORRECTED PROFILE
40.0
0.0
-40.0
INCHES
ERROR
10.0
0.0
-10.0
INCHES
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE FEET X10 1


PROFILE MEASURED WITH ROD AND LEVEL
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABD TEST 1
40.0
0.0
-40.0
INCHES
CORRECTED PROFILE
40.0
0.0
-40.0
INCHES
ERROR
10.0
0.0
-10.0
INCHES
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE FEET X10 1



PROFILE MEASURED WITH ROD AND LEVEL
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABD TEST 2
40.0
0.0
-40.0
INCHES
CORRECTED PROFILE
40.0
0.0
-40.0
INCHES
ERROR
10.0
0.0
-10.0
INCHES
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE FEET X10 1


PROFILE MEASURED WITH ROD AND LEVEL
RUNWAY AT TYNDALL AIR FORCE BASE
LASERS ABD TEST 3
40.0
0.0
-40.0
INCHES
CORRECTED PROFILE
40.0
0.0
-40.0
INCHES
ERROR
10.0
0.0
-10.0
INCHES
0.0
40.0
80.0
120.0
160.0
200.0
DISTANCE FEET X10 1